IN-20
158466
P.125

NASA Contractor Report 191080

Nuclear Engine System Simulation (NESS)

Volume I—Program User's Guide

Dennis G. Pelaccio, Christine M. Scheil,
and Lyman J. Petrosky
Science Applications International Corporation
Torrance, California

March 1993

Prepared for
Lewis Research Center
Under Contract NAS3-25809

National Aeronautics and
Space Administration

CONTENTS

CONTENTS

List of Figures

List of Tables

1.0 INTRODUCTION

An accurate, standalone, preliminary Nuclear Thermal Propulsion (NTP) engine system design analysis tool is required to support current and future Space Exploration Initiative (SEI) propulsion and vehicle design studies. Currently available NTP engine design models are those developed during the NERVA program in the 1960s and early 1970s and are highly unique to that design (see Ref. 1-1) or are modifications of current liquid propulsion system design models. To date, NTP engine-based liquid design models lack integrated design of key NTP engine design features, such as in the areas of reactor, shielding, multi-propellant capability, and multi-redundant pump feed fuel systems. Additionally, since the SEI effort is in the initial development stage, a robust, verified NTP analysis design tool could be of great use to the community.

This effort developed an accurate, versatile NTP engine system design analysis program (tool), known as the Nuclear Engine System Simulation (NESS) program, to support ongoing and future engine system and stage design study efforts. In this effort, Science Applications International Corporation's (SAIC) NTP version of the Expanded Liquid Engine Simulation (ELES) program was modified extensively to include Westinghouse Electric Corporation's near-term solid-core reactor design model. The ELES program has extensive capability to conduct preliminary system design analysis of liquid rocket systems and vehicles. The program is modular in nature and is versatile in terms of modeling state-of-the-art component and system options as discussed in Refs. 1-2 and 1-3. The Westinghouse reactor design model, which was integrated in the NESS program, is based on the near-term solid-core ENABLER NTP reactor design concept (see Ref. 1-4).

This program is now capable of accurately modeling (characterizing) a complete near-term solid-core NTP engine system in great detail, for a number of design options, in an efficient manner. The following discussion summarizes the overall analysis methodology, key assumptions, and capabilities associated with the NESS, presents an example problem, and compares the results to related NTP engine system designs. Initial installation instructions and program disks are in Volume 2 of the NESS Program User's Guide.

2.0 ENGINE SYSTEM MODEL

This section discusses the overall NTP engine system design and performance prediction methodology and the unique model input options associated with NESS. To better understand the operation with NESS it is important that the operator be familiar with the ELES program which is discussed in detail in Refs. 1-2 and 2-1.

2.1 Overall Analysis Methodology

The NESS flow logic is essentially the same as the ELES logic detailed in the ELES Programmer's Manual, Ref. 1-3. A simple summary of the analysis procedure is shown in Figure 2-1, and a detailed flow chart is given in Figure 2-2. Many portions of the code are iterated two or more times to improve accuracy. The key inputs include the thrust level, FVAC and engine cycle type, KCYCLE=1 for gas generator (GG) or =3 for expander (cycle 2 is not available at this time). Also important are the chamber pressure and temperature, PC and TCHAMBER, respectively, flow paths (bypass fractions NFF and BYPTUR), nozzle configuration, NOZTYP and KOOLNZ, and the number of propellant feed legs, NTPA.

Once an input file has been formulated and read in by NESS, the first step is to initialize propellant properties from the libraries of propellant data stored in the code. These properties will be recalculated at many different code locations and for many different conditions throughout code execution. The ideal performance is initially estimated based on known chamber pressure and temperature, and nozzle area ratio; the boundary layer and divergence efficiencies are calculated at this time and an estimated delivered specific impulse (Isp) is found. This estimate is used to calculate a reactor flowrate. The nozzle heat load is estimated as 1% of total reactor power, and this heat load, Isp, and flowrate are passed to the reactor design portion of the code, ENABLER, for calculation of reactor fuel and overall operating characteristics.

The reactor inlet pressure and temperature are now used to calculate the cycle pressure schedule. During the pressure calculations, the nozzle barrier cooling requirement is also calculated along with the regen cooling requirements. Now that all engine efficiencies are known, the actual delivered Isp and flowrate are calculated. The actual nozzle heat load is compared with the original estimate and if they are not within 10%, the code loops back to the reactor design portion of the code and repeats all steps up to the point this comparison is made. If the nozzle heat loads are reasonably matched, but the reactor design has only been performed once, the code loops back to the reactor design with the newly calculated Isp and flowrate to improve accuracy.

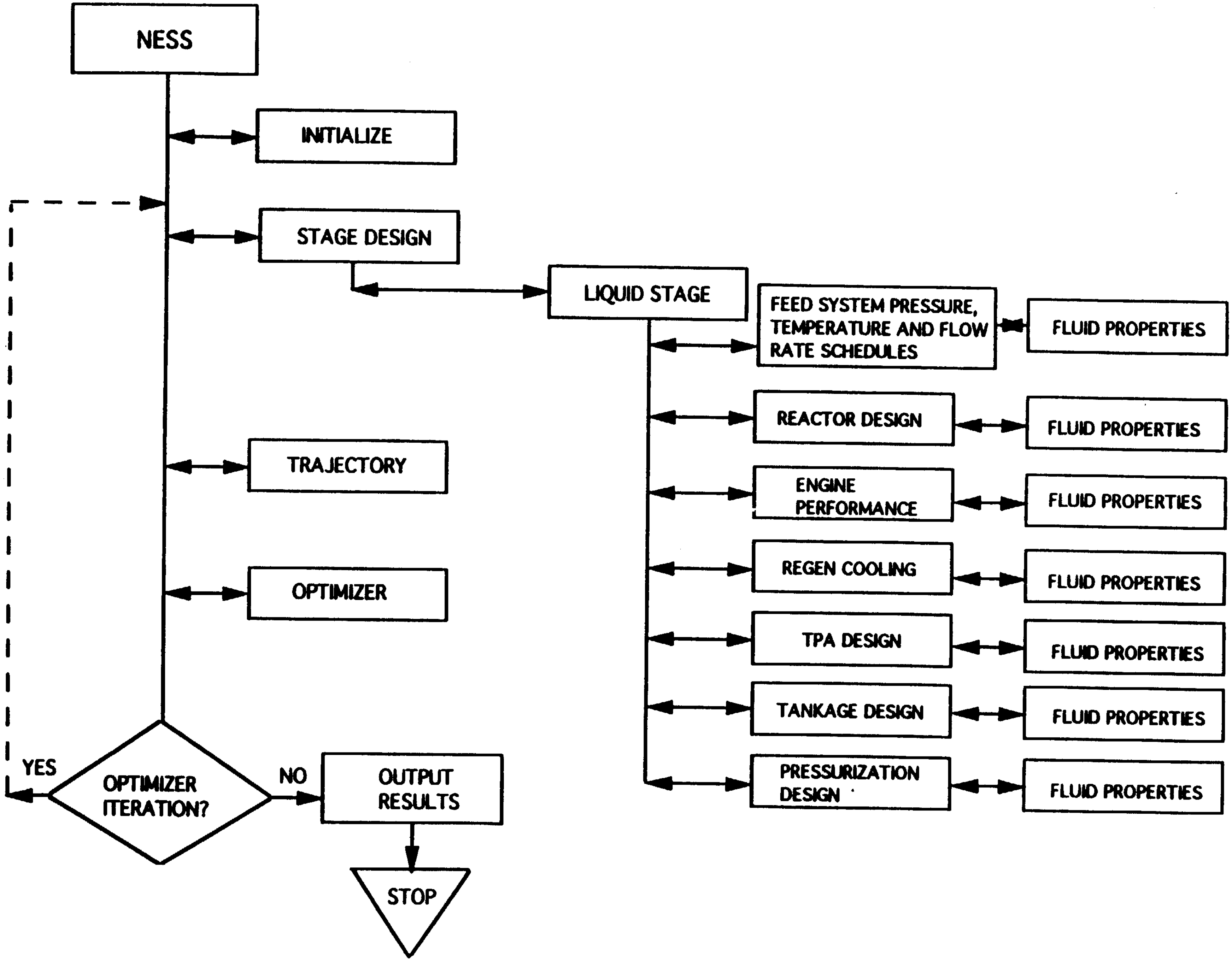

Figure 2-1 NESS Program Overview

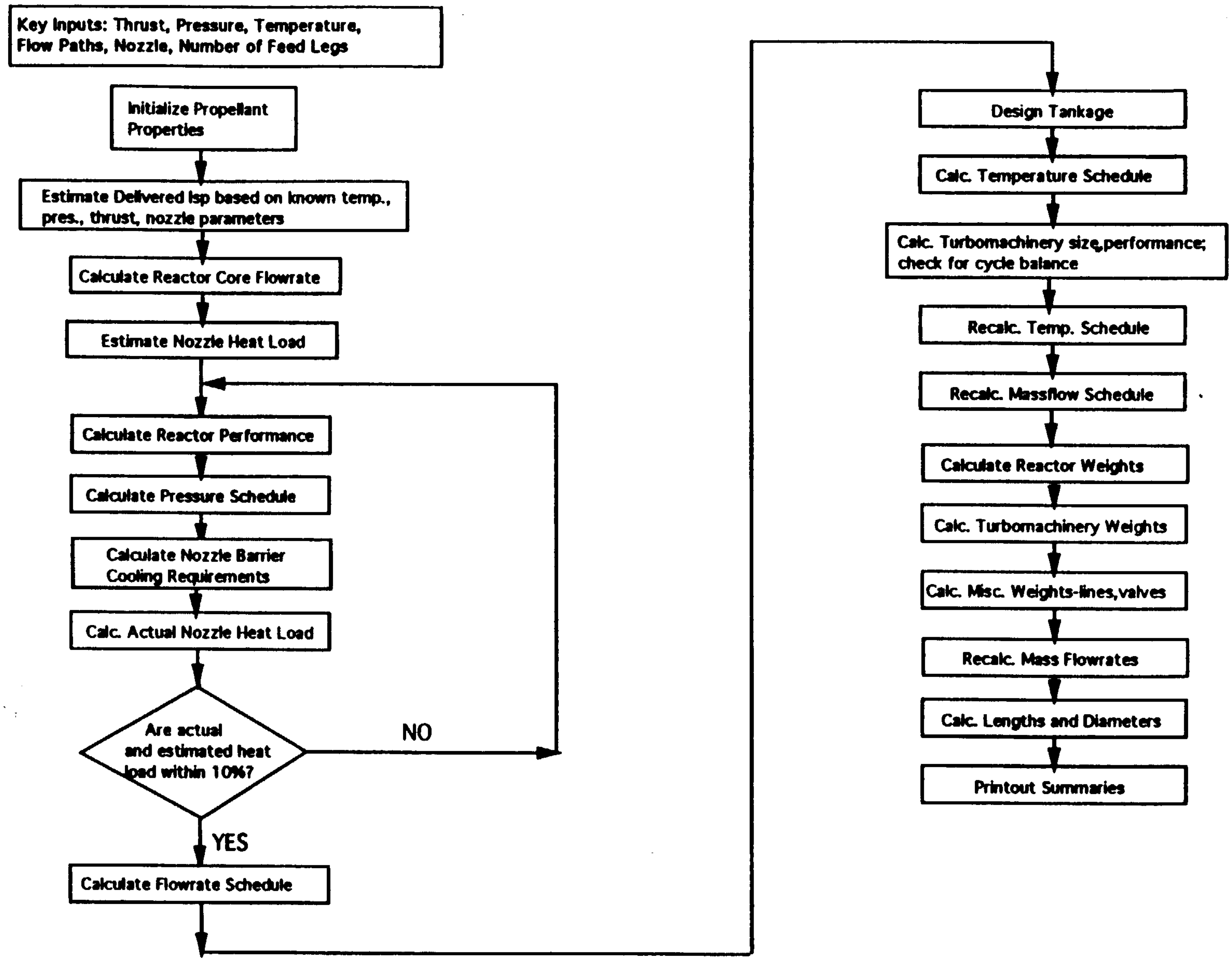

Figure 2-2. NESS Program Flow Logic

After the reactor design, performance, and pressure schedule have been completed satisfactorily, the code now calculates all cycle flowrates. Tankage volumes, pressures, temperatures, and pressurization requirements are calculated next. The temperature schedule is determined, and the turbomachinery can now be analyzed. The turbopump assembly (TPA) portion of the code calculates the size and performance of the pumps and turbines, and checks for cycle balance by comparing pump required horsepower to the turbine delivered horsepower; if not balanced, a new turbine pressure ratio is calculated and the TPA design process is repeated.

Once the TPA design has been completed, the flowrate and temperature schedules are then recalculated to improve accuracy. Next, component weight calculations for the reactor, turbomachinery, nozzle, and all miscellaneous parts (lines, valves, etc) are performed. Mass flowrates are calculated one more time, overall engine dimensions are found, and finally, output summaries are printed out. When the double run option is selected (see Section 2.3.1), the entire design process is completed for an engine at reduced thrust level and then a second iteration of the entire design at full thrust level is performed beginning with the reactor module using some of the values calculated in the first pass (TPA parameters and some weights).

Flow path schematics of the representative NTP expander and gas generator engine cycle systems are shown in Figure 2-3.

2.2 Major Code Components

Table 2-1 lists the major code subsystem modules along with key flags and input variables. Each of these subsystems is discussed in further detail in the sections following, including both overall discussion of the module and how to determine the inputs required.

2.2.1 Engine Performance

Engine performance calculations begin with an ideal one-dimensional equilibrium (ODE) performance value that is later degraded with loss multipliers. The ideal values for Isp and characteristic velocity (C*) are calculated by the ODE module of the Two-Dimensional Kinetic Reference Program (TDK), Ref. 2-1, as a function of chamber pressure, temperature, and nozzle area ratio. Tables of hydrogen performance data are stored in the subroutine HYDROGEN along with the curve-fit equations used to calculate ideal C*, which is a function of temperature and pressure only. An ideal Isp at desired conditions is interpolated from these tables. To run the code with a propellant other than hydrogen, ODE (or a similar code) must be run to generate the tables of Isp data and the C* equations. This data is then put into a new subroutine that is called by the rest of the code when appropriate.

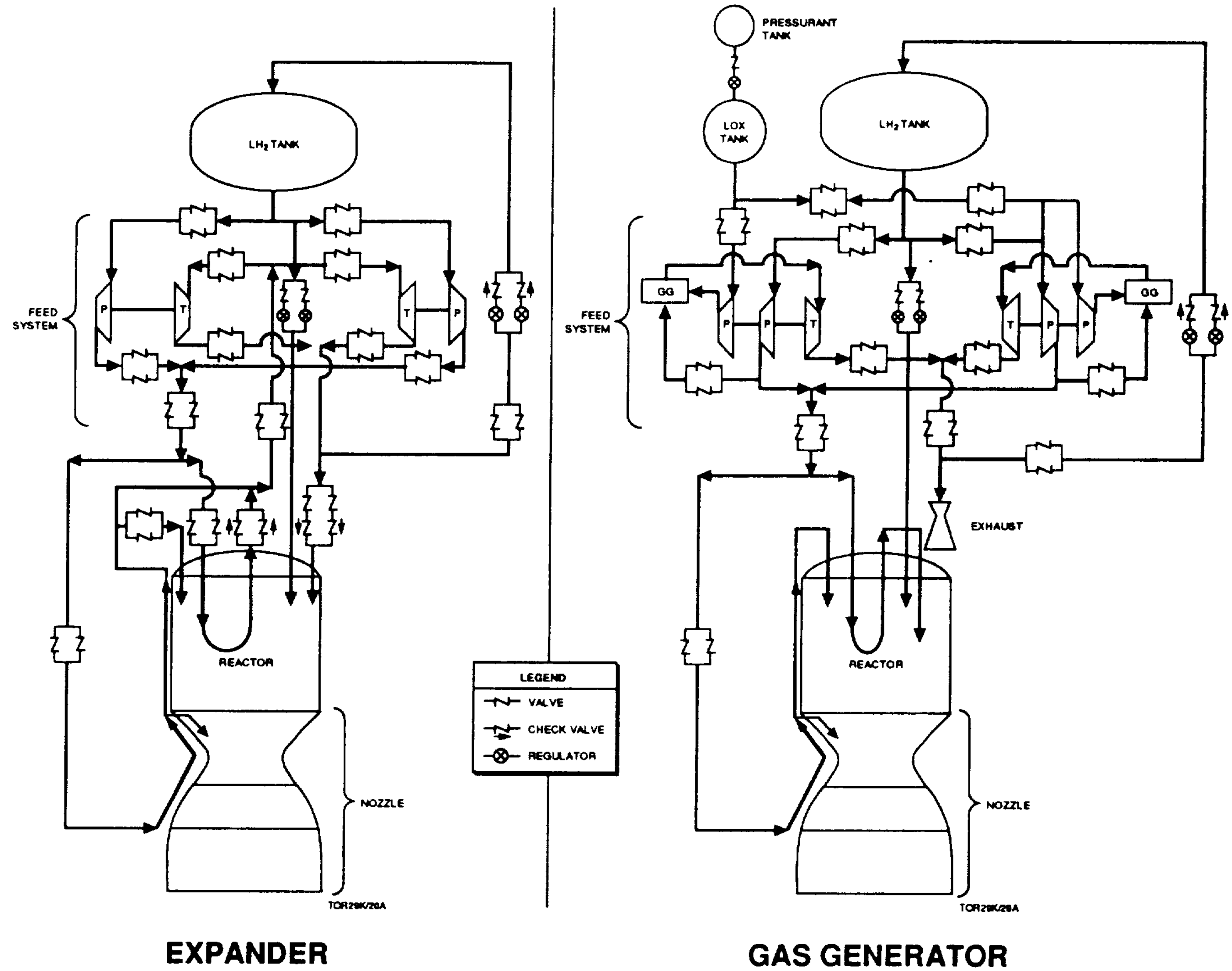

Figure 2-3. Representative NTP Expander and Gas Generator Engine System Cycle Flow Paths

Table 2-1. Key NESS Flags and Input Variables

Module	Variable	Value	Results
General Input:			
Cycle Type	KCYCLE	= 1	Gas Generator Cycle
		= 3	Expander Cycle
Thrust Level	FVAC	–	Set thrust level
Chamber Pressure	PC	–	Set pressure
Chamber Temperature	TCHAMBER	–	Set temperature
Choose double-run?	IDBLRUN	0,1	If =1, double-run used
Input burn time?	IUSRBRN	0,1	If =1, input burn time
User-defined TPA?	ISTSET	0,1	If =1, input TPA values
Nozzle:			
Exit area ratio	EPS	–	Set exit area ratio
Use extension?	KEXNOZ	0,1	If =1, use extension
Use 3-portion nozzle?	NOZTYP	0,1	If =1, use 3-portion nozzle
Attach area ratio 1	EPSATT	–	Set ext. attach area ratio
Attach area ratio 2	EPSAT2	–	Set 2nd ext attach area ratio
Nozzle cooling	KOOLNZ	= 2	Regen cooling of nozzle ext.
		= 3	Trans-regen cooling
		= 4	Radiation cooling
		= 5	Film cooling (GG cycle only)
Regen Cooling:			
Turbine Bypass Ratio	BYPTUR	–	Set turbine bypass flow
Barrier Temp. Fraction	DIFTBF	–	Set barrier temperature
Reactor:			
Fuel Type	FTYPE	= 1	Graphite fuel
		= 2	Composite fuel
		= 3	Carbide fuel
Support Pattern	SPAT	= 2:1	Set support pattern
		= 3:1	
		= 6:1	
Nozzle Flow Percent	NFF	—	Set nozzle/tie tube flows
Tankage:			
Tank Type	NCTNK	= 0	Tandem tankage
		= 1	Non-conventional tankage
Pressurization Method	KGASFL	= 0	Cold helium or solid GG
		= 1	Autogenous
Turbopump Assembly:			
Pump Configuration	JCNFIG	= 1	Gearbox
		= 2	Single shaft TPA
		= 3	Twin TPA in series
		= 4	Twin TPA in parallel
		= 5	Multiple feed leg TPA
Use Boost Pumps?	JBPFL	0,1	If =1, use fuel boost pump
Number of Feed Legs	NTPA	–	Set number of TPA feed legs

The loss multipliers used to degrade the ideal performance are calculated using standard JANNAF procedures, Ref. 2-2, or Aerojet-derived methods, Ref. 1-2. It is assumed that the reactor itself has no losses, and therefore engine efficiency is determined by nozzle-related factors. The efficiencies (or losses) calculated by NESS are the nozzle boundary layer efficiency, divergence efficiency, and nozzle barrier cooling efficiency. The gas generator bleed efficiency is calculated when applicable. A thorough explanation of these efficiencies is given in the ELES Technical Information Manual, Ref. 1-2, and the key equations are summarized below.

The boundary layer loss equation was developed by Aerojet as a result of their experience in defining this loss. The equation is as follows:

$$ETABL = 0.997 - (\ln(EPS)/100)*[1.-0.065*\ln(0.01*Pc*Fvac)+ 0.001*(\ln(0.01*Pc*Fvac))^2]$$

where EPS = Nozzle Exit Area Ratio

Pc = Chamber Pressure (psia)

Fvac = Vacuum Delivered Thrust (lbf)

This equation is accurate for engines with a radiation or film cooled nozzle, but does not take into account the energy returned to the core flow by a regen-cooled nozzle. In this case, the energy lost by the nozzle is retained by the regen coolant flow and fed back into the engine, and therefore should not be considered a true loss. A nozzle that is completely regen cooled should have a boundary later efficiency of 1.0, while a partially regen-cooled nozzle, as is typically used, should have an ETABL less than 1.0, but higher than that predicted by the above equation. To provide accurate modeling of the regen-cooled nozzle option, an input adjustment factor, ADJBL, is applied to the efficiency calculated by the above equation. The adjustment factor is applied as:

$$ETABL = 1.0 - (1.0 - ETABL)*ADJBL$$

The current value used for ADJBL of 0.2 (code default = 1.0) was determined by comparison with Rocketdyne performance values, see Ref. 2-3, which were calculated in much greater detail than is possible with NESS.

The divergence loss is a function of nozzle shape and was derived as curve-fits of the information presented in Appendix A of the CPIA document No. 178, see Ref. 2-4. The equations are as follows:

For conical nozzles:

$$\text{ETADIV} = 0.5 + \cos(\text{alpha})/2. \qquad \text{alpha = half angle in deg.}$$

For RAO contour nozzles:

$$\text{ETADIV} = 1.0 - (1. - C)*[(1.75-\text{RATMLR})/0.75)]^{1.7} \qquad \text{for RATMLR} <= 1.75$$

or

$$\text{ETADIV} = 1.0 \qquad \text{for RATMLR} > 1.75$$

where

$$C = \text{constant} \quad = 0.945 + 0.01*\ln(\text{EPS}) \qquad \text{for EPS} <= 20$$
$$= 0.958 + 0.00566*\ln(\text{EPS}) \qquad \text{for EPS} > 20$$

EPS = Nozzle Area Ratio
RATMLR = ratio of nozzle length to the length of a minimum length RAO nozzle; an input

The divergence efficiency can also be adjusted, if desired, with the input factor ADJDIV used as:

$$\text{ETADIV} = 1.0 - (1.0 - \text{ETADIV})*\text{ADJDIV}$$

The barrier cooling loss is a function of the amount of cold fluid needed to maintain the nozzle wall temperature below the maximum allowable for the material used. Aerojet chose a simplified barrier cooling loss routine consisting of a stream tube analysis which flow-averages the performance of the core stream tube with that of the barrier stream tube. The procedure for calculating stream tube flow areas and flow rates is detailed in the ELES Technical Manual, Ref. 1-2. The maximum barrier temperature is input as described in section 2.2.2, and is used to calculate barrier Isp and C*, and ultimately barrier mass flux. The fraction of fuel used for barrier film cooling (FFFC) is calculated as:

$$\text{FFFC} = \text{barrier flowrate}/(\text{barrier flowrate} + \text{core flowrate})$$

The barrier loss (ETABAR) is set at 0.95 and is put into the comprehensive barrier cooling loss equation:

$$\text{ETAMRD} = [(\text{Isp}*\text{mdot})_{\text{core}} + (\text{Isp}*\text{mdot}*\text{ETABAR})_{\text{barrier}}]/(\text{Isp}*\text{mdot})_{\text{total}}$$

where all Isp's are ideal.

This efficiency can be adjusted by the input ADJMRD in the same form as that used for the boundary layer and divergence losses. Note that the "barrier cooling loss" is referred to as the "mixture ratio maldistribution loss" in the ELES manuals.

For gas generator cycles, the gas generator bleed efficiency is calculated as a function of the bleed nozzle flowrate, pressure, and area ratio. It can be adjusted with ADJGGB in the form:

ETAGGB = ETAGGB * ADJGGB

All other efficiencies described in the ELES Technical Manual, Ref. 1-2, were set equal to 1.0 because of their inapplicability to the nuclear engine; for example, injector or fuel and oxidizer mixing efficiencies.

2.2.2 Nozzle Cooling

The nozzle can be cooled by a number of methods. The converging portion of the nozzle, including the throat, is automatically regen cooled. It is of milled slot construction to upstream area ratio of 4 with an adapter of regen tubes connecting the nozzle to the reactor. The remainder of the nozzle is cooled by regen tubes, radiation, a cold film of turbine exhaust (GG cycles only), or by a combination of these. A detailed explanation of regen cooling calculations is given in the ELES Technical Information Manual, Ref. 1-2, and Section 2.2.3 of this report gives nozzle modeling options.

The nozzle regen cooling requirements are based on the nozzle wall material properties, chamber temperature, regen coolant flowrate, regen inlet temperature and pressure, and regen channel size. The maximum wall material temperature in input as TGWNOM and is the temperature above which the material will begin to degrade. For copper, a common converging nozzle material, this maximum temperature is 1460°R. The 1460°R temperature limit is typical of that used for the maximum design nozzle wall temperature for the Space Shuttle Main Engine (SSME) which is made of NARLOY-Z, a copper alloy, Ref. 2-5. For the high chamber temperatures typical of nuclear reactors, the regen coolant is unable to maintain this max wall temperature if the fluid on the other side of the wall is at chamber temperature. Therefore, a small amount of cool fluid from the regen outlet is dumped into the chamber at the top of the converging nozzle and is used to form a cool barrier between the wall and the hot core fluid. The loss in efficiency due to this barrier cooling is detailed in the Section 2.2.1 and in the ELES Technical Manual, Ref. 1-2. The greater the temperature mismatch between the barrier fluid and the core fluid, the larger the cooling loss, and therefore the highest possible barrier fluid temperature should be chosen that can still maintain the required material wall temperature. The barrier temperature is input as a relation between the core temperature and max wall temperature, TGWNOM. The input variable DIFTBF is used as follows:

$$T_{barrier} = TGWNOM + DIFTBF*(T_{core} - TGWNOM)$$

Ideally, DIFTBF = 1.0 and the barrier temperature equals the core temperature to minimize flow losses. If DIFTBF = 0.0, the barrier temperature is set equal to the maximum wall temperature. For a copper wall with max temperature 1460°R and a core temperature of 4860°R (2700 K), the maximum barrier temperature that could still maintain the required wall temperature is 1630°R, which means the input DIFTBF = 0.05. A good value for DIFTBF can really only be determined by past experience and trial and error; the larger the difference between the maximum wall temperature and the core temperature, the lower the value for DIFTBF will have to be.

Other key regen cooling inputs include the gas wall material thermal conductivity and minimum gauge. The land width (WLTHR) and channel width (WTHR) of the regen cooling channels at the throat are also important inputs because they will strongly affect the regen pressure drop, i.e. small channels => high velocity => large delta P. There is also an option for user-input regen pressure and temperature drops, initiated with the flag INDPDT set equal to 1 and DELTAT and DELTAP input.

2.2.3 Nozzle Design Modeling Options

The user has a number of different nozzle modeling options. The most basic option is to set the nozzle extension flag KEXNOZ to zero and have regen slots all the way out to the exit area ratio EPS. This type of nozzle is almost never used in practice because of excess weight, and therefore a nozzle extension option is allowed. If the nozzle type flag NOZTYP is set to zero and KEXNOZ = 1, an extension will be added to the regen slots. This section extends from area ratio EPSATT to EPS, and can be regen, radiation, or film cooled (GG cycles only), with cooling option selected with the variable KOOLNZ. The new and final option is for NOZTYP=1, which models a three-section nozzle made up of regen slots, regen tubes, and a radiation cooled extension. The user must set KEXNOZ = 1, KOOLNZ = 2 (regen tubes in portion 2), and area ratios EPS, EPSATT (attach point of second section) and EPSAT2 (attach point of third section). Figure 2-4 shows the three nozzle modeling options and key input variables.

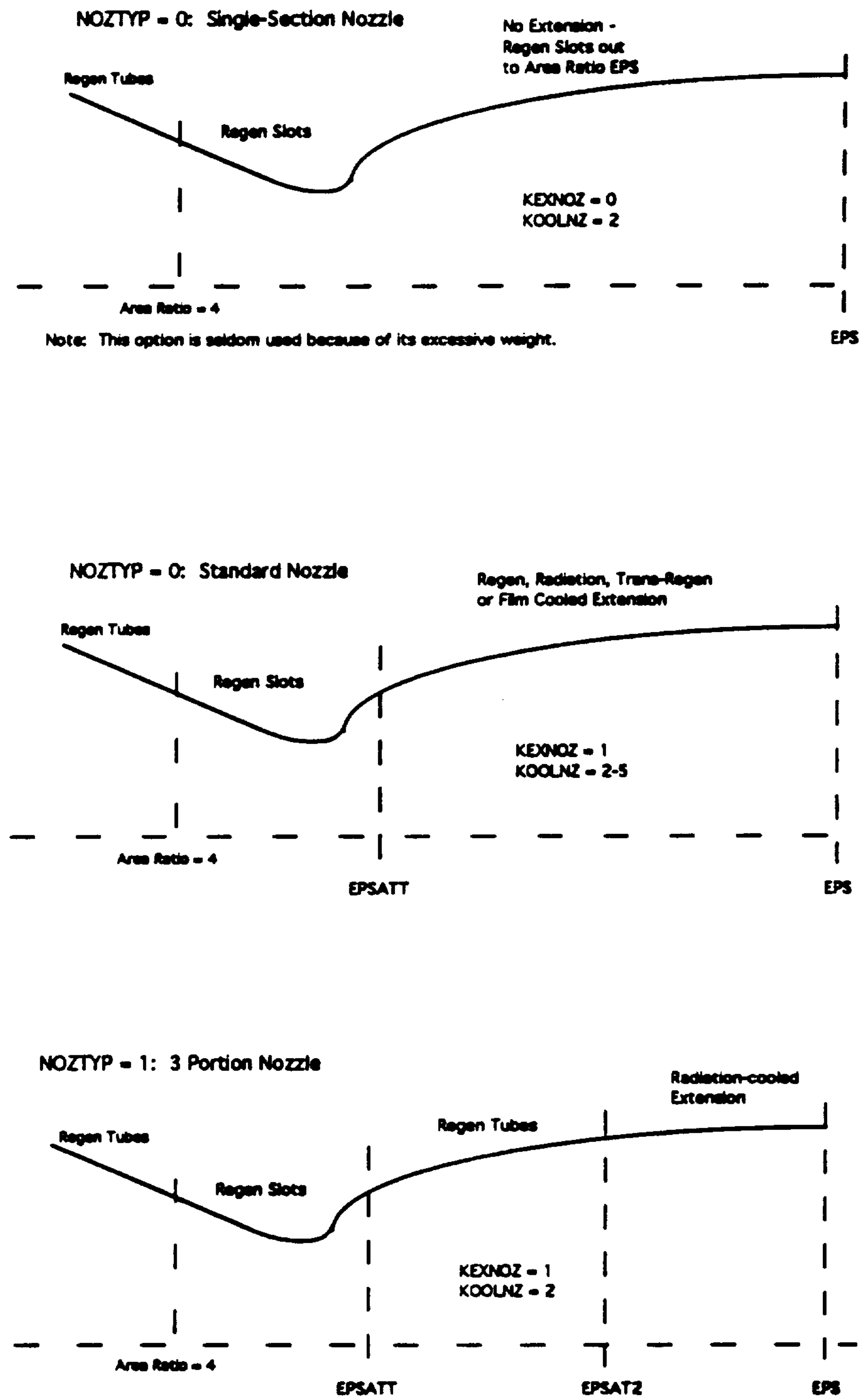

Figure 2-4. Nozzle Modeling Options and Key Input Variables

The regen slot portion of the nozzle extends out to an upstream area ratio of 4 where it attaches to a nozzle/reactor adapter that is made of aluminum regen tubes covered by a load-bearing casing of aluminum. The weight of this assembly is calculated in the reactor weight subroutine, and is included in the reactor pressure vessel weight.

Material density and strength are input for the converging nozzle, first nozzle extension, and second nozzle extension with RHCSTR, RHONZE, RHONZ2 and SIGCHM, SIGNZE, SIGNZ2, respectively. The minimum thicknesses of the two possible extensions are input as TNZMIN and TNZMN2. The volume of material used for the regen slots is calculated and the total converging nozzle weight is a function of this volume, the density of the material used for each region of the slots, and total surface area. The weight of the regen tubes is a function of the maximum pressure in the tubes, surface area, and material density, strength, and minimum gauge. The radiation-cooled extension weight is simply a function of surface area and material density and thickness.

2.2.4 Reactor

A near-term solid core, ENABLER reactor module was developed by Westinghouse and integrated with ELES to form NESS. The reactor design is made up of two segments: the first calculates fuel requirements and reactor operating conditions, the second calculates about 30 reactor component weights along with key reactor dimensions. NESS provides hydrogen data, Isp, core flowrate, and nozzle heat load to the reactor module (ENABLER) for its calculations. In return, ENABLER provides the reactor inlet and tie tube outlet conditions needed for pressure and temperature schedule analysis. A detailed discussion of the reactor model can be found in Section 3.

One key reactor input is the nozzle flow fraction, NFF, which determines the percentage of flow going to the tie tubes and to regen cooling. The user also selects the fuel type as either graphite, composite, or carbide using the variable FTYPE. SPAT is used to select the support pattern as 2:1, 3:1, or 6:1. The reactor temperature is input as TCHAMBER, and is used extensively in the reactor design process, along with determining the overall engine performance. As can be seen in the worksheet, the user can input a number of variables related to heat pickup in various sections of the reactor, as well as several fuel element characteristics.

2.2.5 Auxiliary Components

The category "auxiliary components" consists of instrumentation, a pneumatic supply system, thrust structure, gimbal, and reactor cooldown assembly. Previously in ELES, some of these component weights were calculated as a percentage of the total engine weight, some were a function of thrust only, and some were not calculated at all. Also, these weights were originally calculated assuming a standard liquid rocket engine rather than a nuclear rocket engine.

NESS auxiliary component weights are based on work previously performed by TRW, Ref. 1-1, which includes equations for various nuclear rocket engine auxiliary component weights. These correlations relating component weight to reactor power were developed as curve fits of NERVA-type reactor data. The TRW equations applicable to the ENABLER-type rocket engine design have been programmed into NESS and include:

Instrumentation:	weight = 166.9 + 0.00743*P - 1.64E-7*P^2
Pneumatic Supply System:	weight = 751.6 - 0.00208*P + 2.35E-6*P^2
Reactor Cooldown Assembly:	weight = 238.1 + 0.0254*P - 8.04E-7*P^2
Upper Thrust Structure:	weight = 786.25 = 0.1868*P + 5.2E-5*P^2
Lower Thrust Structure:	weight = 492.9 + 0.0911*P + 1.463E-6*P^2

where P = power in MW

The upper and lower thrust structures are combined into the "thrust mount" weight. The other three weights make up the "support hardware weight".

Although these equations provide a useful starting point for auxiliary component weight calculations, they represent NERVA-era technology rather than state-of-the-art designs. To account for advances in technology, weight multipliers are input that decrease these weights to values more in line with current engine designs. The instrumentation multiplier, CXWINST, is left at 1.0. The pneumatic supply system weight was compared with similar system weights on current engines, such as the SSME, and was found to be extremely high, see Refs. 2-5 and 2-6. It should be noted that the TRW pneumatic supply system weight correlations assume that the complete pneumatic supply is part of the NTP engine system, while for the SSME the main supply is located in the Space Shuttle. This is one major contributor to the weight difference as well as the higher pressure and lighter weight components associated with today's systems. Therefore, the pneumatic system weight multiplier, CXWPNEU, is input as 0.25. The reactor cooldown assembly multiplier, CXWTNKAS, is input as 0.9 to account for technology advances. The thrust structure multiplier, CXWTHM, is set to 0.9 to allow for lighter weight materials and improved technology. If NERVA-era technology is desired, all above multipliers should be input as 1.0.

2.2.6 Materials of Construction

The NESS user is allowed to select the material of construction of all major subsystem components. Standard library tank materials include 6061-T6 aluminum and 6Al-4V titanium, or the user may input density, strength, and minimum gauge for a previously undefined material. A discussion/comparison of candidate cryogenic tank materials is given in the ELES Technical Information Manual, Ref. 1-2. The input worksheet includes a table of the most common engine materials along with their densities and strengths. This data is typically used for valves, nozzles, lines, and regen channels, and the user may input data for any unlisted material desired. The nozzle designs also require input of minimum material thicknesses. The turbine blade strength and density, as well as an overall TPA density that is used in pump and turbine weight calculations, can also be input.

2.2.7 Tankage

The main tankage options in NESS are either tandem tankage, in which fuel and oxidizer are stacked on top of each other to fit within a common shroud, or non-conventional tankage, where the user selects the number of tanks as well as their shapes and placement on the stage. The tandem tanks option should probably not be used for nuclear thermal rockets because they use only hydrogen as propellant, and may carry only a very small amount of oxidizer for use with a gas generator. The tandem tank model automatically calculates an oxidizer tank weight even if the amount of oxidizer carried is very small or zero, and this tank is sized to fit in the tank shroud with a diameter based on the size of the large fuel tank. The non-conventional tankage design option should give a better estimate of actual tank sizes.

The tank sizes for both tank geometries are dependent on amount of burned propellant, ullage fractions, acquisition system design, residual propellant, propellant boiloff, and autogenous pressurization. The approach taken in sizing the propellant tanks is as follows:

1) Amount of fuel burned is input; calculate amount of oxidizer burned in GG if necessary.

2) Add weight of autogenous pressurization requirements to each propellant

3) Calculate the tank free volumes using the propellant densities and ullage fractions

4) Calculate propellant residuals and acquisition device volumetric displacement based on tank free volume estimate

5) Calculate tank surface area as needed for heat transfer calculations to determine propellant boiloff

6) Total tank volume is now calculated as the sum of the above volumes: burnt propellant, ullage, residuals, boiloff, autogenous pressurant, and acquisition devices

These tank volumes are now used to determine pressurization requirements and update initial estimates.

The large variety of possible tandem tank configurations is shown in the ELES Technical Information Manual, Ref. 1-2, along with the equations used to calculate many of the tank dimensions and volumes. All tanks can be cylindrical, spherical, or elliptical (CSE tanks), and the non-conventional tankage option allows toroidal tanks as well. Non-conventional tank weights are calculated from an ideal tank weight through the use of a tank non-optimum factor, which is defined as the ratio of actual tank mass to ideal tank mass. The ideal tank mass is based on tank wall thickness and size. The actual mass includes any additional material required for weld lands and fittings. For conventional tanks that require feedlines, supports, pressurization, and a propellant management device, a tank non-optimum factor of 1.7 is suggested. Different factors are recommended for different tank types, and these factors are listed in Table 7.3.1.1 of the ELES Technical Manual, Ref. 1-2. The tank non-optimum factor is input as the variable CXWTNK.

When preparing inputs for tankage design, the user must first set the variable NCTNK equal to either 0 for tandem tanks or 1 for non-conventional tanks. If tandem tanks are chosen, the user now determines such factors as arrangement of propellant (fuel forward or aft, etc), common or separate dome tanks, monocoque or suspended arrangement, tank head ellipse ratio, tank dome orientation, safety factor (SFFLTK, SFOXTK, SFPRTK), and tank material (MTNKFL, MTNKOX, MATPT).

To use the non-conventional tank option, the user should first sketch the arrangement of tanks and engines on the stage. The total number of non-conventional tanks is input with NTANKS (includes oxidizer, fuel, and pressurant). The type of fluid contained within each tank is input with the variable INTNK1-4, where an input of 1 is for oxidizer tanks, 2 is fuel, 3 is pressurant. For example, if two oxidizer and two fuel tanks are desired, input INTNK1 = 1,2,1,2. This indicates that tanks 1 and 3 are oxidizer tanks, and tanks 2 and 4 are fuel tanks;

retain this same numbering scheme when defining the remaining tank parameters. Input the tank ellipse ratio for each tank with ELTNK1-4. The tank type is selected as either CSE or torus with the variable KTANK1-4. The angular location of each tank gives its relative position on the stage and is input as TANGL1-4. Tank radial location indicates the tank distance from the center of the stage, RADLO1 = 4*1.0 places all four tanks at the edge of the stage and RADLO1 = 0. places a tank at the center of the stage. Engine angular and radial locations are input similarly with the variables ENGAN1-4 and ENGRD1-4. The material for each tank is selected with the variable MATNK1-4. Tank safety factors are input with SFTNK1-4, and tank weight multipliers are input with CXNCT1-4. More input variables for each tank geometry are contained in the worksheet.

The forward and aft skirt length inputs are actually input as fractions of tank lengths. For tandem tankage, both aft and forward skirt lengths should be input as 1.0 to form a skirt fully covering both tanks. To shroud non-conventional tankage, the forward skirt should be set to 0.0 and the aft skirt length should be 1.0. This will yield a skirt that covers all tankage and is as long as the tallest non-conventional tank. DMOTOR is used to input the stage diameter.

2.2.7.1 Tank Heat Transfer. For the long duration missions proposed for nuclear rockets, tank heat transfer and insulation are important aspects of vehicle design. A detailed discussion of this area is provided in the ELES Technical Information Manual, Ref. 1-2, and includes information on optimizing insulation thicknesses.

NESS offers four possible tank heat transfer scenarios: ignore tank heat transfer, external boundary exposed to conductive source, worst case solar radiation, and ground hold ice formation. The desired option is selected with the variable KHXOPT. The most common options are either to ignore heat transfer (when tank design is not important) or worst case solar radiation. The solar radiation option requires input of insulation characteristics, space hold time, flight time, average orbital distance from earth, and earth and solar heat flux parameters. The insulation is typically composed of a layer of spray-on foam insulation (SOFI) plus a multi-layer insulation (MLI) blanket. The density, thermal conductivity, and thickness of each type can be input. Table 2-2 lists these values for a variety of types of MLI.

2.2.7.2 Propellant Tank Pressurization. Propellant tanks can be pressurized by cold helium gas, a solid gas generator, or autogenously. The method of pressurization is selected with the variables KGAS, KGASFL, and KGASOX as shown in the worksheet. The selection of a propellant acquisition device, either some sort of bladder or surface tension device, has a strong effect on the pressurization calculations. An extremely detailed discussion of tank pressurization is presented in the ELES Technical Information Manual, Ref. 1-2.

Table 2-2. Multi-Layer Insulation Data Comparison

MLI Configuration	No. (cm)	No. (in)	Kg (m^3)	Lbm (ft^3)	Watts (m-K)	BTU (hrft°R)
DAM/DBL silk net	19.7	50.0	45.2	2.82	$4.5x10^{-5}$	$2.5x10^{-5}$
DAM/Tissue glass	39.4	100.0	51.9	3.24	$2.5x10^{-5}$	$1.4x10^{-5}$
SAM Crinkled	15.7	40.0	14.6	0.91	$4.7x10^{-5}$	$2.6x10^{-5}$
DAM/SGL Nylon Net	31.5	80.0	53.8	3.36	$3.0x10^{-5}$	$1.7x10^{-5}$
DAM/Dexiglass	23.6	60.0	58.8	3.67	$5.0x10^{-5}$	$2.8x10^{-5}$
DAM Crinkled/Tissue glass	23.6	60.0	31.1	1.94	$7.0x10^{-5}$	$3.9x10^{-5}$
Superfloc	11.8	30.0	13.8	0.86	$4.5x10^{-5}$	$2.5x10^{-5}$

When cold gas pressurization is selected, KGASFL,KGASOX = 0 and KGAS = 2, the user also inputs the cold helium storage pressure as PICG and the helium tank final pressure fraction, FPULCG, where a value less than 1.0 indicates a blowdown tank. If KGAS is set equal to 1 instead of 2, a solid gas generator will be used which requires fairly extensive user inputs regarding solid fuel characteristics and burn rates (see worksheet). If KGASFL, KGASOX are set to 1, the tanks will be pressurized autogenously. This option has an advantage over helium pressurization when the additional weight of the evaporated propellants is less than that of the helium storage vessel, as occurs in pump fed stages with low NPSH requirements. The propellant used in autogenous pressurization will be bled off from various points in the flow depending on the type of cycle being used; this pressurant flow is taken from the turbine exhaust in expander cycles, and from turbine exhaust and pump outflow (oxidizer side) for the gas generator cycle.

2.2.8 Propellant Pressure/Temperature/Flowrate Schedules

The propellant pressure, temperature, and flowrate are calculated at key points within each engine cycle. The pressure schedule is calculated "backwards", beginning with the chamber pressure and working back up through the cycle using input and calculated pressure changes. The temperature and flowrate schedules begin at the tank outlet and flow down through the cycle to the reactor inlet conditions. ELES can evaluate pressure-fed, gas generator, staged reaction, expander, and staged combustion cycles, but NESS can handle only expander and gas generator cycles at this time.

The expander cycle flow paths are shown in the schematic in Figure 2.3. The tank outflow is divided into tie tube and regen/reflector flow based on the input flow fraction, NFF. The regen flow is used to cool both the nozzle and reflector, with a small amount bled off to form a cool barrier inside the nozzle. The reflector outflow can be either dumped directly into the core or used to run the turbine. Reflector outflow going to the turbine is mixed with the tie tube flow, and turbine inlet temperature is calculated as a massflow averaged combination of the tie tube and reflector flows, i.e.

$$T_{\text{turbine inlet}} = [(T*\text{mdot})_{\text{reflector}} + (T*\text{mdot})_{\text{tie tube}}]/\text{mdot}_{\text{turbine inlet}}$$

Turbine outflow is dumped into the reactor core, with a small amount bled off for autogenous pressurization if needed.

The key pressure calculations for the expander cycle are the turbine and reflector outlet pressures. The reactor inlet pressure and temperature are calculated by the reactor model, and are therefore known. The tie tube pressure drop is fixed by Westinghouse at 250 psia, and the reflector pressure drop is 25 psia. The reflector, turbine, and reactor pressures are related by:

$$(P*\text{mdot})_{\text{core inlet}} = (P*\text{mdot})_{\text{reflector to core}} + (P*\text{mdot})_{\text{turbine to core}}$$

Using the relations below, equations for reflector and turbine outlet pressures as functions of known or estimated quantities only can be derived:

PTURBI, PTURBO = turbine inlet and outlet pressures, respectively
PREFI, PREFO = reflector inlet and outlet pressures, respectively
PTTI, PTTO = tie tube inlet and outlet pressures, respectively
PREGI, PREGO = regen inlet and outlet pressures, respectively
PCI = core inlet pressure
PVLVFO = main valve outlet pressure
TURBPR = turbine pressure ratio
FLOW = reactor flow rate
TTFLOW = tie tube flow rate
WDTRIF,WDTROF = turbine inlet and outlet flow to core, respectively
WDREFT = reflector outflow to turbine
WDBYPF = reflector outflow to core = turbine bypass flow

PTURBO = PTURBI/TURBPR

= (PREFO*WDREFT + PTTO*TTFLOW)/(TURBPR*WDTRIF)

= (PCI*FLOW - PREFO*WDBYPF)/WDTROF

PTTO = PTTI - 250

PREFO = PREFI - 25

PTTI = PVLVFO = PREGI

PREFO - PREGI = total delta P = regen delta P - 25 = DELPTOT (regen delta P < 0)

Substitution gives:

$$\text{PREFO} = \frac{\text{PCI*TURBPR*WDTRIF*FLOW} + (\text{DELPTOT} + 250)\text{*TTFLOW*WDTROF}}{\text{WDREFT*WDTROF} + \text{TURBPR*WDBYPF*WDTRIF} + \text{TTFLOW*WDTROF}}$$

PTURBO = (PCI*FLOW - PREFO*WDBYPF)/WDTROF

Once the reflector outlet pressure is known, the reflector inlet pressure, which equals the regen outlet pressure, can be calculated so that the regen cooling analysis can be performed and all other pressures in the cycle can be calculated. For multiple feed leg TPA designs, the individual turbine flow rates are multiplied by the number of legs to accurately calculate the pressures. An estimate for DELPTOT is used on the first of many calls to the pressure schedule routine, and is later updated after calls to the regen routines.

The gas generator bleed cycle flow schematic shown in Figure 2-3 uses small amounts of oxidizer and fuel to feed the gas generator that drives the turbine. The turbine exhaust is either dumped overboard through a small bleed nozzle or is dumped into the main nozzle for film cooling. Although this exhaust dump results in a performance loss, the GG cycle has the advantages of relatively simple cycle design (TPA and regen design are not coupled) and lower pump discharge pressures. Since the turbine is powered by the GG, the reflector and tie tube flows are dumped directly into the reactor core, which leads to an equation for reflector outlet pressure of the form:

PREFO = [PCI*FLOW + (DELPTOT + 250)*TTFLOW]/(WDBYPF + TTFLOW)

where all variables are as defined above. As in the expander case, once the reflector outlet pressure is known, the regen cooling analysis can be performed and all other pressures calculated. At this time, the gas generator cycle cannot have multiple feed legs.

For all engine cycles, tank outflow is equal to the core flowrate plus the nozzle barrier flowrate, autogenous pressurant flowrate, and gas generator flow.

2.2.9 Propellant Properties

Propellant properties are required over a very wide range for the variety of models used in NESS, including both gas and liquid phases. The approach used to obtain these values is to begin with a known value of the propellant property at some reference point, and then scale that value to some other condition based on empirical or theoretical correlations. The exceptions to this method include hydrogen and helium, which require separate, extensive data bases from which desired values are interpolated. A detailed discussion of the methods used to determine property data can be found in the ELES Technical Information Manual, Ref. 1-2. Hydrogen data is stored in the routine H2DATA.

An option exists in ELES that allows for user-defined propellants, which requires that the user input certain propellant properties and then select a propellant from the existing ELES library that the new propellant is most similar to. The code next evaluates this new propellant performance based on comparison with the chosen similar propellant. This option is set up for use by non-nuclear bipropellant systems, and therefore cannot be used for reactor designs without major code modification. Hydrogen is currently the only propellant with full performance data tables programmed into the code, and the current method of determining Isp is different than that used for bipropellants and may not be compatible with the old user-defined propellant evaluation methods.

2.2.10 Turbopump Assembly

The purpose of the turbopump assembly (TPA) model is to determine the size, weight, and performance of all pumps and turbines for expander or gas generator cycles. NESS offers the following turbomachinery configurations:

1. Single turbine driving a gearbox which powers an oxidizer and fuel pump on a common shaft.
2. Single turbine driving oxidizer and fuel pumps on a common shaft.
3. Twin TPA's, series drive fluid flow.
4. Twin TPA's, parallel drive fluid flow.
5. Multiple propellant feed leg TPA - each leg is identical and sees 1/NTPA of the flow (expander only)

The desired option is indicated with the input variable JCNFIG. If the multiple feed leg option is chosen (JCNFIG=5), the number of feed legs is input as NTPA. Boost pumps may be included in the propellant circuit by setting JBPFL, JBPOX=1, with the boost pump fraction of total propellant head rise input as BPFRFL, BPFROX.

NESS checks the necessity for pump or turbine staging, allowing up to four stages for pumps and two for turbines. To avoid unrealistic designs, the code checks the maximum allowable tip speeds and the turbine blade root stresses. Pump head coefficients and pump and turbine efficiencies are calculated from tables included in the program. A partial admission turbine is designed if blade height falls below 0.3 in. The equations used to design the pumps and turbines are given in the ELES Technical Information Manual, Ref. 1-2.

An engine cycle is considered balanced when the ratio of required pump horsepower to delivered turbine horsepower is approximately equal to 1.0. If the cycle is not balanced, a new value for turbine pressure ratio is calculated and the entire design process is repeated.

An important input for expander cycle TPA design is the turbine bypass ratio, BYPTUR; it is the ratio of reflector outflow that goes directly to the core divided by the total reflector outflow. The tie tube flow goes directly to the turbine and is therefore not affected by this bypass. As the bypass ratio acts only on the reflector flow, the user must be careful when determining this value. For example, if an overall turbine bypass of 50% is desired and the nozzle flow fraction is 0.70 (30% of flow goes to tie tubes, 70% to nozzle), the turbine bypass ratio BYPTUR is calculated and input as 0.5/0.7 = 0.71.

The gas generator cycle requires input of the GG mixture ratio, OFGGPB, the ratio of specific heats, GAMGPB, the specific heat, CPGGPB, and the molecular weight, WMGGPB. The default values for these variables are for LO2/H2 at approximately 1400 psia. The ratio of specific heats, specific heat, and molecular weight were determined by a run of the ODE module of the TDK computer code using the desired pressure and mixture ratio. The user can also input the turbine outlet pressure, PTURBO, and the pressure ratio across the gas generator/pre-burner, PBPFR, PBPRO.

The multiple propellant feed leg TPA option (JCNFIG=5) was added to ELES to allow for the redundancy usually desired in nuclear rocket engines. It is available for the expander cycle only at this time. Typically, two feed legs will be desired, with one half of the total flow running through each pump and turbine during normal operation, as can be seen in the expander cycle schematic in Figure 2-3. This option is normally used with the double run option as described in Section 2.3.1. When multiple feed legs are used, the TPA output lists the weight for each pump and turbine in their corresponding sections, while the TPA summary section lists weights for the total system.

Another new code option is the evaluation of a user-defined TPA, which is described in detail in Section 2.3.3. This option allows evaluation of off-design pump and turbine performance. It is used automatically with the double run option in which turbomachinery is designed at a pump-out thrust level and then multiple pumps and turbines possessing the previously determined characteristics are evaluated at full thrust level. The flag to initiate the user-defined TPA design option is ISTSET = 1, and INPTPA = 1 indicates that TPA-related weights will be input.

2.2.11 Weight Multipliers

Due to the wide range of possible design strategies available for most engine components, weight multipliers are provided for all major components. These multipliers are useful when trying to match existing designs or design methods. They are also used to account for excess component weight not specifically calculated in the code; for example, the standard tank weight multiplier is 1.7 to allow for the extra material required for weld lands and fittings, see Ref. 1-2. Some of these weight multipliers have been discussed in detail elsewhere in this report; all will be summarized here.

The weight multipliers are listed in the worksheet along with their default values. All tank-related multipliers are set to 1.0 as NESS will primarily be used for engine design; the user must input any desired value other than this default. The total nozzle and hardware multiplier, CXWENG, is set to 1.0 as it is more likely that the multipliers for individual components will be used to account for extra weight rather than adjusting the entire engine weight. The valve multiplier, CXVALV, is set to 2.8 to account for dual valves (for redundancy) and a factor of 1.4 to include some extra valve weights (other than the main valve) not explicitly calculated in NESS. The convergent nozzle multiplier, CXWCHM, is set to 1.0. CXWNZE is the nozzle extension multiplier and is used on all portions of the nozzle extension (tubes + radiation-cooled portion when used); its value of 1.1 allows for flanges and fittings.

Hot gas ducting weight is adjusted with CXWDUC that is set to a value of 3.5 to account for the weight of flanges, bolts, bellows, bosses, insulation, etc. The gimbal system (excluding the power supply) is multiplied by a factor of 1.4 as set by the variable CXWGIM. The thrust mount multiplier CXWTHM is set to 0.9 to allow for technology advances not included in the NERVA-era weight correlation between thrust structure and reactor power. The gas generator injector weight is multiplied by 1.4 as input by CXWIGG. Each component of the turbopump assembly (pumps and turbines) is multiplied by a factor of 1.3 using CXWTPA as was deemed necessary after comparison with other engine designs. The same reasoning holds for the ignition system multiplier CXWIGN with a value of 1.3. Engine bay lines are multiplied by 2.5 to allow for flanges, bolts, bellows, etc. The TPA components, valves, and engine bay lines are all multiplied automatically by the number of propellant feed legs, NTPA, when appropriate.

The support hardware multipliers, CXWPNEU, CXWINST, and CXWTNKAS, are discussed in the support hardware section of this report, and reflect the technology advances made since the correlations used to calculate the component weights were developed.

2.3 New Features

A number of features have been added to the original ELES to more accurately model a nuclear thermal propulsion system.

2.3.1 Double-Run Option

A typical nuclear propulsion system will include multiple propellant feed legs for redundancy. Each feed leg will be designed to a desired pump-out thrust level that is less than the nominal operating value. To accurately model this feature, a computer run would have to be made at this reduced thrust level to design/size a single pump and turbine for these conditions, and then these values would be used for a second run at full thrust level with multiple pumps to determine nominal operating conditions. To simplify this process, a double-run option is available for the expander cycle. The first pass through the code designs a single shaft turbopump that operates at a reduced thrust level (pump-out conditions) specified by the user. The second pass automatically assigns the pump and turbine parameters calculated by the first run to be inputs for the user-defined TPA option. The valve and engine bay line weights from the first run are also retained to be output with the total engine summary. The second pass will design a system using an input number of identical propellant feed legs, each with characteristics as calculated in the first pass.

To utilize this option, the input file must contain IDBLRUN = 1 and a corresponding thrust level fraction FFRAC (default = 0.8, or 80% thrust level). The user must set the pump configuration flag to the single shaft option, or JCNFIG = 2; the code automatically sets JCNFIG

= 5 and assigns the pump and turbine parameters calculated in the first pass to the appropriate user-defined TPA variables for the second pass. In the input file, the user specifies the number of identical feed legs to be used for the second pass as NTPA.

2.3.2 User-Defined Engine Burn Time

An option has been added which allows the user to input the engine burn time rather than have the code calculate the burn time based on flowrates and input amount of propellant. This option is useful when the amount of propellant to be used is unknown or the tankage design is not important. This burn time is used mainly to size the gimbal power supply, whose weight is time-dependent. To use this option, set the flag IUSRBRN equal to 1 and then input burn time in seconds as TUSRBRN.

2.3.3 User-Defined Turbomachinery

The user-defined turbomachinery option of NESS allows evaluation of pump and turbine performance at off-design operating characteristics and with a variety of propellants. The parameters input to define the TPA for off-design evaluation are detailed in the worksheets following, and include number of stages for all pumps and turbines, pump and turbine diameters, turbine annulus area, turbine admission fraction, and various gas generator parameters.

NESS calculates pump head rise and volumetric flowrate, and turbine horsepower, mass flowrate, and pressure ratio based on cycle balance requirements. Using these values, the pump rpm is calculated as a function of input pump diameter. To perform this calculation, a correlation had to be developed for pump head coefficient as a function of specific speed (standard cases interpolate this coefficient from a data table), and is of the form:

$$HC = const * SS^{x}$$

where

HC = head coefficient

SS = pump specific speed

For example, the main pump correlation is:

$$HC = 3.7852 * SS^{-0.28786}$$

This correlation is different for main pumps and boost pumps. The specific speed is a function of pump rpm, head rise, and volumetric flowrate, as is shown below:

$$SS = RPM * SQRT(volumetric\ flowrate)/(pump\ head\ rise^{0.75})$$

The pump diameter is calculated as:

$$Dia = (720/pi*RPM) * SQRT(32.2*pump\ head\ rise/head\ coefficient)$$

Substituting the head coefficient and specific speed equations into the equation for pump diameter and rearranging gives an equation for pump rpm's as a function of input pump diameter only. Once the rpm's are known, the specific speed, efficiency, and horsepower are easily found from the standard ELES equations.

The user-defined TPA option of NESS calculates the required turbine mass flowrate and horsepower and then evaluates the user input turbine to see how well it performs in meeting these requirements. The first step is to calculate the isentropic spouting velocity (Co) based on the number of turbine stages. Now calculate the ratio of turbine blade tangential velocity to Co based on input turbine diameter (U/Co) and check whether this ratio is within the accepted range of 0.2 - 0.6; if not, print a warning. Next, calculate the turbine inlet mach number and check whether it is below the accepted maximum value of 1.7; issue a warning if not. Finally, calculate turbine specific speed, efficiency, and horsepower provided. Compare the horsepower provided with the horsepower required and if not within 3%, calculate a new turbine pressure ratio and repeat the entire process.

To use this option, first set the variables ISTSET = 1 and INPTPA=1 to indicate that the TPA is user-defined and the TPA-related weights will be input. The number of pump stages are input with PDIAFL and PDIAOX. Turbine stages are input with either TSTGES for a single shaft turbine, or TSTAGF and TSTAGO for fuel and oxidizer turbines (can be used only for GG cycles). Diameters are input in inches with PDIAFL and PDIAOX, and either TDIAM or TDIAFL and TDIAOX. Boost pump diameters can be input with BPDIAF and BPDIAO. Turbines also need to have admission fraction and annulus area input using the variables listed in the worksheet. TPA-related weights will not be calculated for the user-defined TPA option and therefore the user may input these weights for total TPA, TPAWT, start system, WSTART, ignition system, WIGNIT, hot gas manifolding, WHGMF, autogenous heat exchanger, WTHTX, and gas generator/preburner, WGGPB. If not input, the weight summaries will list these weights as zero.

The user-defined gas generator requires many more inputs than are required for the expander cycle. First set the flag IUSRGG equal to 1 to indicate a user-defined GG and input all pump and turbine parameters as described above. In order to insure that the GG and turbine are modeled correctly, the turbine inlet and outlet pressures, PUSRTI and PTURBO, respectively, must be set to the values calculated/input for the NESS-calculated case. For example, if a NESS-calculated GG cycle using LOX/H_2 is designed at 80% thrust level and is next to be evaluated at 50% thrust level, the turbine inlet and outlet pressures calculated by NESS in the first run must be used as inputs for the user-defined run. The turbine inlet temperature, TUSRTI, should be set to the actual value found for the propellant combination at given mixture ratio and pressure; normally this temperature will simply be the same as that found in the 80% run. If a different propellant is to be evaluated or the GG is being input based on an existing design (not NESS-generated), this temperature can be found most easily by an initial NESS run where the user-defined option is not used and the GG is at conditions similar to those to be used for the actual user-defined run. The turbine flowrate, although listed as an input, is actually calculated by NESS as the correct amount of fluid flow required for the given operating conditions. The GG bleed flowrate, Isp, and efficiency can be set to any reasonable values.

2.3.4 Weight Margin

The user may now input a fraction of the total non-nuclear weight to be added in as a margin weight. Inside the code, non-nuclear weight is the sum of nozzle weight, total TPA weight, lines, valves, thrust mount, support hardware, and total gimbal system. The percent (fraction) of this weight to be used as margin is input with FMARG, whose default is 0.02 (2% margin). In the output summary, the "non-nuclear weight" includes the weight margin.

2.4 Code Setup and Execution

NESS is written in FORTRAN 77 and currently resides on a VAX mainframe computer system. The entire code is made up of four parts: the source code, the executable, the library of subroutine object files, and a library of propellant performance data. The source code for NESS is made up of 219 subroutines that have been separated into individual files for easier editing. These subroutines take up approximately 4000 blocks of storage space. The object library ELES_LIB.OLB takes up about 5900 blocks of storage space. The propellant performance library is included with the code, but may not be needed as all hydrogen performance data has been entered elsewhere in the code; this data file uses 940 blocks of storage. If storage space is a problem, the executable alone could be loaded onto the computer to take up about 4400 blocks of storage, while the rest of the code is left on tape to be loaded as needed.

When loading NESS onto a new computer system, a fairly structured series of directories must be set up for proper execution. The executable and propellant data file must be put into a directory called [account name.ELES]. The input files reside in the directory [account.ELES.INPUT], and the output appears in the directory [account.ELES.OUTPUT]. The source code and object file library are loaded into [account.TEMP.CURRENT]. If the code will be run in debug mode, a directory [account.TEST] must be set up and the input file must be put in this directory with the name ELES.INP.

A number of *.com files are included along with the code itself. ELES_SETUP.COM must be run at some point before the code is run to insure proper directory and file initialization; this is most simply achieved by adding this file to the LOGIN.COM file and having it execute automatically with each login. In the [..CURRENT] directory, the file FL.COM is used to compile an individual subroutine and add/replace it in the object library; it is used as '@FL filename'. FALL.COM will recompile all subroutines and replace their previous versions in the object library. To link the governing routine with the object library, type '@LD' and LD.COM will be executed and a new executable version will be created.

All input filenames must have the extension '.inp' and the names must contain 10 characters or less, excluding the extension. To run the code, type 'MODEC' filename without the filename extension of .inp; for example, typing 'MODEC NTPREGEN' will run NESS with the input file NTPREGEN.INP and place the output in a file called NTPREGEN.OUT in the output directory. A file called NTPREGEN_ELES.OUT is also created in the output directory that is essentially a printout of the input file. If the computer has a debug mode, enter the [account.TEST] directory and type 'RUN ELES:MODEC.EXE/DEB' and the code will execute using the input file ELES.INP stored in that directory.

3.0 REACTOR SYSTEM

This section describes the Westinghouse ENABLER NTP reactor system including its internal shield, modeling assumptions, and scaling relations.

3.1 Reactor System Description

An engineering description of the ENABLER reactor's major subassemblies is given in the following sections.

3.1.1 Reactor Assembly

The reactor assembly consists of a nuclear reactor and an actuation system for reactivity control devices with associated instrumentation and controls are shown in Figure 3-1. The reactor consists of fuel elements, support elements, a core periphery, support plates and plena, an internal shield, a reflector assembly, and control drum drive assemblies. Reflector coolant is provided from the nozzle coolant channel exhausts. The support stem coolant exhaust is mixed with the reflector coolant flow at the reflector outlet and is used as drive power for the engine turbopump. The turbine exhaust gas flows through the dome flow baffle, internal shield, plena between the core support plate and the internal shield and reactor core, and through the reactor core. This gas is heated by the reactor assembly to operating temperatures and exhausted out the nozzle.

3.1.2 Fuel and Support Elements

The fuel elements shown in Figure 3-2 for the ENABLER reactor serve the combined function of providing the energy for heating both the hydrogen propellant and the required heat exchanger surfaces. The energy is provided through the fission of ^{235}U contained in the fuel element. Table 3-1 lists the characteristics of the three fuel materials defined in the NESS code. Multiple coolant channels coated with ZrC (for graphite and composite) form flow passages through the elements. The exterior surfaces of the hexagonal fuel elements (except carbide) are also coated with ZrC. This coating protects the carbon from reaction with the hydrogen propellant.

Longitudinal support for the reactor is obtained by tie-tubes running the full length of the reactor. These tie-tubes are located inside unfueled support elements, which have the same length and external dimensions as the fuel elements. A single, large longitudinal hole in these support the

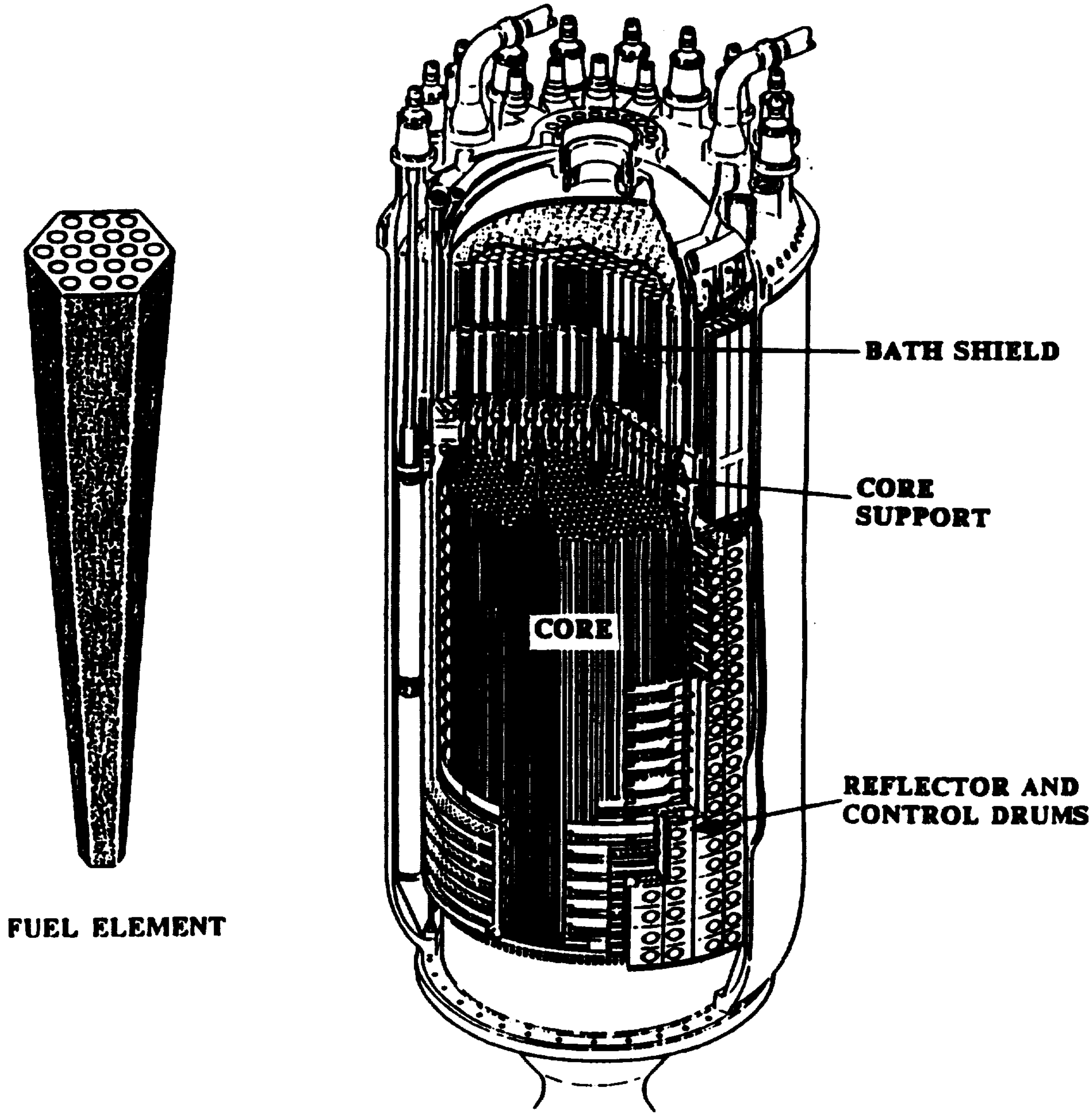

Figure 3-1. ENABLER (NERVA Type) Nuclear Thermal Rocket Engine

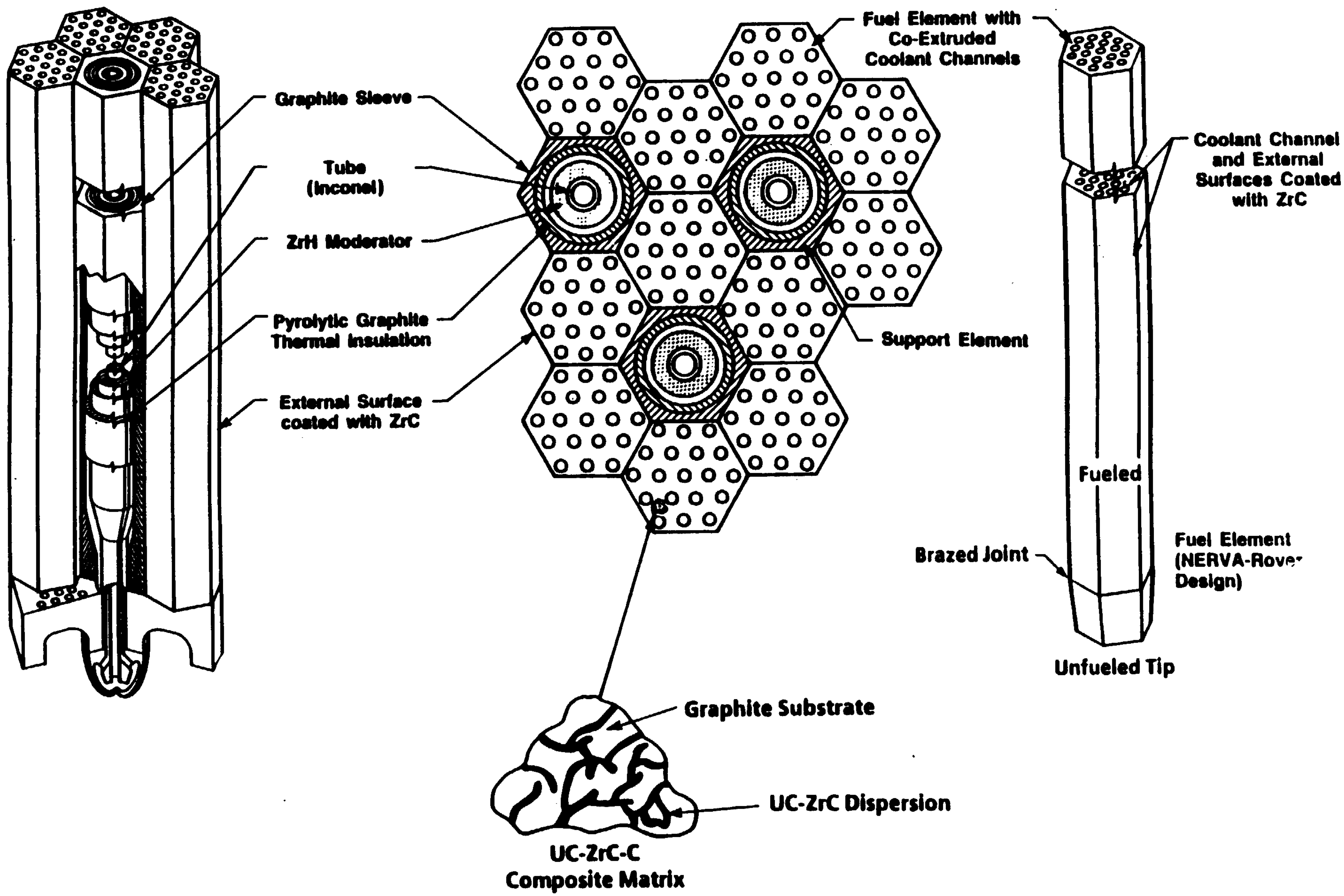

Figure 3-2. Prismatic Fuel Elements and Supports

fuel elements. A single, large longitudinal hole in these support elements contains the tie-tube assembly, ZrH_2 moderator, and a porous ZrC insulator. The support element composition is given in Table 3-1.

Table 3-1. Fuel and Support Element Parameters

Fuel Element Composition	**Graphite**	**Composite**	**Carbide**
Temperature Range (°K)	2200-2500	2500-2900	2900-3300
Fuel	Coated Particle	UC . ZrC Solid Solution and Carbon	(U,Zr) C Solid Solution
Coating	ZrC	ZrC	—
Unfueled Support Element Composition	Graphite	ZrC-Graphite Composite	ZrC
Unfueled Element Coating	ZrC	ZrC	—

The reactor core is sized based on an average fuel element power of 1.2 MW per element and one support element per six fuel elements as shown in Table 3-2 at thrust levels greater than 50,000 pounds. The 1.2 MW per fuel element was demonstrated in the Pewee reactor (402 fuel elements with a power level of 503 MW) and was the design level for the Phoebus-2A reactor (4068 fuel elements with a 5000 MW design power level). For the smaller reactors, sufficient reactivity is obtained by increasing the relative number of support elements to fuel elements, see Table 3-2, which increases the amount of zirconium hydride moderator to the desired level. Also to keep a reasonable core length to diameter ratio (<2) for the smaller reactors (15000-25000 lbf thrust) the element length was set at 35 inches. At the 25000 thrust level (Pewee size core volume) the relative power density of the fuel element is the same as the larger reactors (1.2 MW/52 inch). However, at the lowest thrust level (15,000 lbf) the fuel element power density had to be reduced in order to obtain a core large enough for criticality.

Table 3-2. Reactor Parameters as a Function of Thrust Level

Thrust (lbf)	15,000	25,000	>50,000
Reactor Power Range	275-400	460-670	920-6700
Fuel and Support Element Length (inch)	35	35	52
Pressure Vessel Length (inch)	82.6	84	101.6
Fuel Element Power (MW)	0.629	0.808	1.20
Relative Fuel Element Power Density	0.778	1.0	1.0
Ratio of Fuel Elements (N) to Support Elements	2:1	3:1	6:1

3.1.3 Radiation Shield

A radiation shield internal to the pressure vessel is used to reduce the gamma and neutron flux levels in the engine components forward of the reactor. This internal shield limits radiation leakage through a plane 63 inches forward of the core center, perpendicular to the engine axis, to the levels given in Table 3-3. This requirement is the same as that used for the NERVA program. The shield is located immediately upstream of the core support plate, see Figure 3-1. The reactor internal shields for the thrust levels over 50,000 lbs. have about 12.5 inches of Borated Aluminum Titanium Hydride (BATH) and about 1.3 inches of lead. At the lower thrust levels the thickness of the BATH and lead is slightly reduced due to lower core power density.

Table 3-3. Radiation Leakage Limits at a Plane 63 Inches Forward of the Core Center

Type of Radiation	Radiation Leakage Limits Within Pressure Vessel Outside Radius
Gamma Carbon KERMA Rate	1.8×10^7 Rad(c)/hr
Fast Neutron Flux	2.0×10^{12} n/cm^2-sec
Intermediate Neutron Flux	3.0×10^{12} n/cm^2-sec, 0.4 eV $\leq$ En $\leq$ 1.0 MeV
Thermal Neutron Flux	6.0×10^{11} n/cm^2-sec En < 0.4 ev

3.1.4 Reactor Propellant/Coolant Circuits

In an NTP system, a nuclear reactor supplies the energy to heat the propellant flowing through the engine. The hot propellant flows into a nozzle that functions in the same manner as a chemical engine. The reactor in an NTP engine system generally has three propellant (coolant) circuits as shown in Figure 3-3. The primary circuit is through the central shield and core into the chamber. This circuit provides more than 90% of the heat to the propellant. All the components surrounding the core require cooling due to the radiation induced heating and heat transfer from the primary stream. The propellant cooling of the ex-core components is divided into two additional circuits: the tie tube (core support) circuit and the peripheral component circuit that includes the core reflector and extension shield. These circuits along with the nozzle regenerative cooling circuit provide the first pass through the reactor system for the propellant, which acts as component coolant. The heat supplied by these secondary circuits provides the energy to power the turbopump. After passing through the turbine, all the propellant passes through the primary core circuit and into the nozzle to provide the engine thrust.

HEAT GENERATION	
Core	~1,500 MW
Tie Tubes	3-7%
Reflector	1-2%
Central Shield	~0.2%
Ext. Shield	~0.03%

COMPONENT BLOCK DIAGRAM

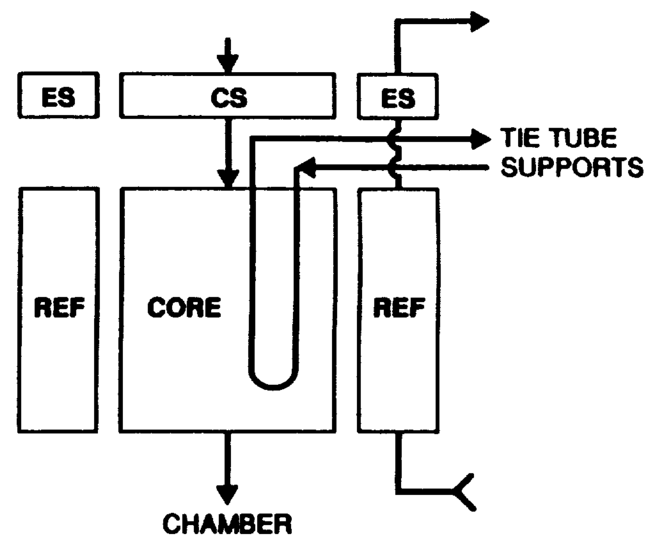

Figure 3-3. Propellant Flow Circuits Through the Reactor

3.2 Baseline Reactor Design

The Rover/NERVA database provides numerous reference designs for reactors and engines in the size range of 15 Klbf to greater than 250 Klbf thrust range. The engine modeled in the NESS program is the ENABLER class of NTP engine systems, which is discussed in Ref. 1-4, that is derived from the nuclear rocket technology developed in the Rover/NERVA programs. The ENABLER designs incorporates NERVA type fuel elements which are 19 mm (0.75 inch) hexagonal extrusions of graphite based fuel with a 19 coolant channel array within the element. The code allows the user to select from one of the three fuel materials developed during the Rover/NERVA program: Graphitic, Composite, or Carbide. The ENABLER engine is generally specified with fuel elements fabricated from the (U,Zr)C-Graphite composite material developed late in the Rover/NERVA program, which exhibits improved corrosion resistance and allows higher operating temperatures and power densities, see Refs. 3-1 and 3-2. Zirconium-hydride moderator is placed in the core support elements (demonstrated in the Pewee reactor) to increase the neutronic reactivity and thereby decrease the required uranium fuel loading.

Detailed data is available on the breakdown of actual reactor system component masses. In the NESS model the core size is based on the number of fuel elements needed to meet the required power level. The design of the reactor peripheral regions follows the R-1 engine design shown in Figure 3-4, but the peripheral components are sized according to the core dimensions. For the R-1 reactor shown in Figure 3-4, the nominal core dimensions are 38 inches diameter by 52 inches long. The components surrounding the core are sized to satisfy structural and neutronic

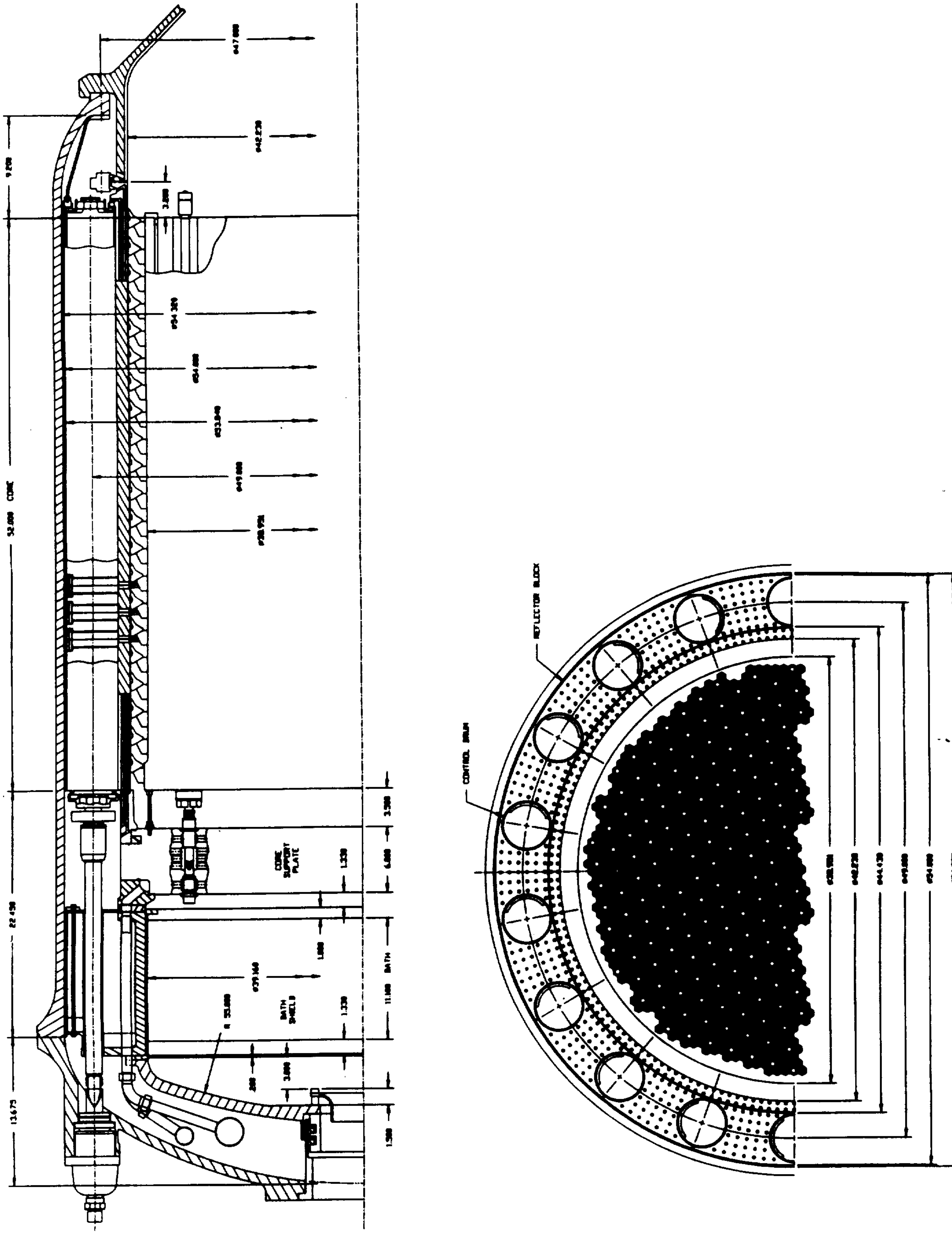

Figure 3-4. Layout Drawing of the R-1 Reactor

requirements. The major components are the core barrel, reflector, pressure vessel, core support plate, flow baffles, and top shields.

3.3 Reactor Core Design and Thermal-Hydraulic Model

The required core power level is determined from the specified engine flow and chamber temperature. The core power level and the average allowable heat generation of a fuel element determines the total number of fuel elements and support elements in the core. Based on the core peaking factor, a single channel analysis is performed to calculate the thermal and pressure profile for the peak channel of the peak element in the core. The calculation uses finite increments along the channel length beginning at the core exit where the chamber conditions are specified. The governing equations are given below.

The convective heat transfer between the fluid and channel wall is defined by:

$$q = h_c A_s (T_w - T_r)$$

where T_w is the channel wall temperature and T_r is the coolant gas stagnation recovery temperature. For small subsonic Mach numbers (<<1.0) the difference between the recovery temperature (T_r) and the fluid free stream bulk temperature (T_b) is not significant, so that the equation may be written as:

$$q = h_c A_s (T_w - T_b)$$

The heat transfer (q) must match the heat generation in the fuel material. The heat generation in the fuel is determined by the fuel loading, fuel volume, and neutron fluence. For the purposes of the thermal hydraulic calculations it is sufficient to specify a power profile and the total power produced by the element. The NESS code uses a cosine power profile typical of that observed in the NERVA reactors:

$$P = P_n \cos(0.891 \pi (x/L - 0.452))$$

where P_n is the normalized element power factor and x/L is the normalized axial location in the core measured from the inlet. The peak temperature in the fuel (T_f) is determined from the following correlations for a heat generating solid with a hexagon array of coolant channels of diameter D and pitch S:

$$\varepsilon = \frac{\pi D^2}{3.4641\, S^2}$$

$$K = \frac{D}{4}\left(\frac{1}{\varepsilon} - 1\right)$$

$$\psi = \left(\frac{S}{2}\right)^2 \left(0.55133 \ln\left(\frac{S}{D}\right) + 0.25\left(\frac{D}{S}\right)^2 - 0.23446\right)$$

$$T_f - T_w = \frac{q_i \psi}{K\, k_s}$$

where k_s is the thermal conductivity of the solid.

The convective heat transfer coefficient, h_c, is determined by the McCarthy-Wolf, Ref. 3-3, correlation:

$$h_c = 0.025 \frac{k_b}{D} Re_b^{0.8}\, Pr_b^{0.4} \left(\frac{T_b}{T_w}\right)^{0.55} \left(1 + 0.3\left(\frac{x}{D}\right)^{-0.7}\right)$$

where the fluid properties are evaluated at the fluid bulk temperature. The entrance effect term $(1 + 0.3 (x/D)^{-0.7})$ is limited to 1.1 for small x.

As the coolant flows along the channel, it experiences a pressure loss due to wall friction and fluid acceleration. The momentum equation for one dimensional flow in finite increment form is:

$$P_i - P_{i+1} = \frac{G_n^2}{g}\left(v_{i+1} - v_i\right) + f_i \frac{G_n^2\, \Delta x}{g\, D_h}\left(v_{i+1} + v_i\right)$$

where P_i is the coolant pressure at station i, G_n is the mass flow per unit area, v_i is the specific volume of the coolant, D_h is the hydraulic diameter of the channel, f_i is the Fanning friction factor, and Δx is the length increment along the channel. The friction factor is obtained from the Taylor correlation, see Ref. 3-4, for gaseous flow through a smooth tube:

$$f = \left(0.0014 + \frac{0.125}{Re_w^{0.32}}\right)\left(\frac{T_b}{T_w}\right)^{0.5}$$

where Re_w is a modified surface Reynolds number in which the gas density is evaluated at the fluid bulk temperature, but the viscosity is evaluated at the channel wall temperature:

$$Re_w = \left(\frac{G_n D}{\mu_w}\right)\left(\frac{T_b}{T_w}\right)$$

The evaluation of these equations for the peak channel in the core determines the required core pressure drop.

After the calculation of the core profile and pressure drop, the heat generation rates for the core peripheral regions are calculated. Because NESS does not have neutronics analysis capabilities, the heat generation in the peripheral regions is defined as a fraction of the total core power. After completion of the thermal hydraulics, code control returns to the NESS engine code for determination of the cycle balance.

3.4 Reactor Weight Model

The reactor mass model divides the reactor system into 53 regions in an R-Z model as shown in Figure 3-5 and Table 3-4. Each region contains one, or at most a few, components. The masses of all the components and their constituent parts within a region have been tallied and converted into a pseudodensity for each region, given in Ref. 3-5. The dimensions of the regions are based on the core size determined above, with appropriate dimensional dependency algorithms. The pseudodensity is applied to each region to yield the mass schedule of the reactor for everything out to and including the pressure vessel. Thrust structure, turbopumps, and nozzle masses are not calculated in this module; the NESS code determines the balance of engine masses, which is discussed in Section 2.0.

3.5 Design Variable Options

User inputs can be divided into three categories: engine parameters, reactor parameters, and fuel element parameters. The primary engine parameters are thrust level, chamber temperature, chamber pressure, and nozzle expansion ratio. These primary variables are used by the code to

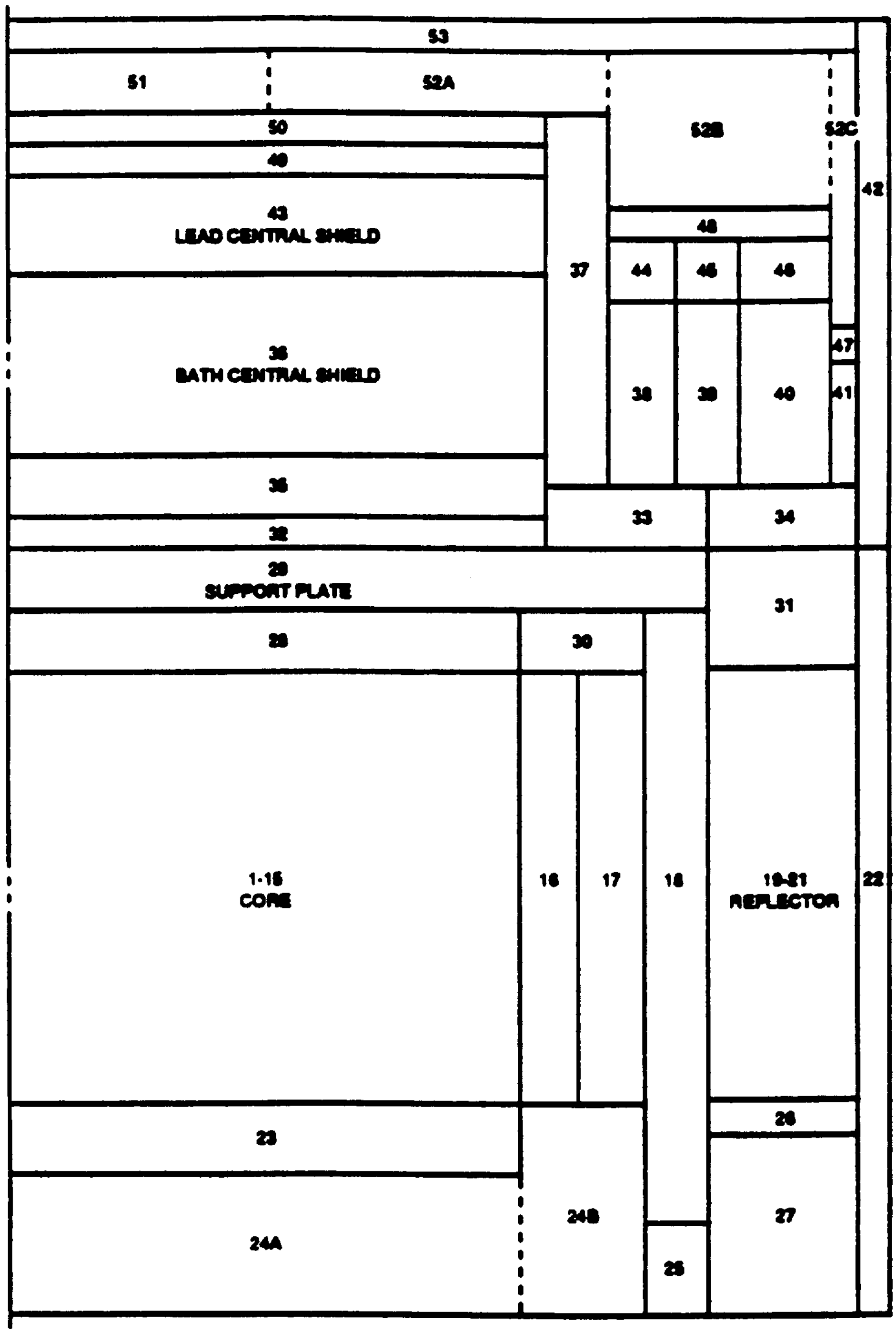

Figure 3-5. R-Z Model of the Regions in the R-1 Reactor

Table 3-4. Reactor Weight Model Regions

REGION NUMBER	REGION DESCRIPTION	MATERIAL
1 - 15	Core	Fueled Element Unfueled Element Pyro Sleeve A-286 SS-304 Hydrogen
16	Core Periphery	Graphitite-G Pyrofoil ZrC (60% Dense) TZM Moly Hydrogen
17	Lateral Support	P03 Graphite ZTA Graphite Pyrofoil Hydrogen
18	Structure	P03 Graphite Al-6061 A-286 Hydrogen

TOR29K/14

Table 3-4. Reactor Weight Model Regions (Cont.)

REGION NUMBER	REGION DESCRIPTION	MATERIAL
19 - 21	Reflector	P03 Graphite Pyrofoil Beryllium Al-6061 A-286 Control Vane Hydrogen
22	Pressure Vessel Side A	Al-7039 Hydrogen
23	CHESH	Pyrographite Pyrofoil NbC/C Comp. W-ThO_2 A-286 SS-304 SS-316 Hydrogen
24	Nozzle Chamber	Hydrogen
25	Nozzle Barrel	SS-347

TOR29K/15

Table 3-4. Reactor Weight Model Regions (Cont.)

REGION NUMBER	REGION DESCRIPTION	MATERIAL
26	Aft Reflector Hardware	Al-6061 A-286 SS-440C Hydrogen
27	Aft Reflector Plenum	Hydrogen
28	Core Plenum	TZM Moly Copper-Boron A-286 SS-302 SS-304 Hydrogen
29	Support Plate	Pyrofoil Al-6061 A-286 SS-302 SS-304 Hydrogen
30	Lateral Support-Forward	Al-6061 A-286 Hydrogen

TOR29K/16

Table 3-4. Reactor Weight Model Regions (Cont.)

REGION NUMBER	REGION DESCRIPTION	MATERIAL
31	Forward Reflector Hardware I	Al-6061 A-286 SS-304 SS-440C Hydrogen
32	Support Plate Plenum	A-286 SS-304 Hydrogen
33	Instrumentation Ring	Al-6061 SS-304 Hydrogen
34	Forward Reflector Hardware II	Al-6061 A-286 SS-304 Hydrogen
35	Aft Central Shield Plate	Al-6061 Hydrogen
36	BATH Central Shield	BATH Al-6061 Hydrogen

TOR29K/17

Table 3-4. Reactor Weight Model Regions (Cont.)

REGION NUMBER	REGION DESCRIPTION	MATERIAL
37	Flow Baffle I	Al-6061 SS-304 Hydrogen
38	BATH Peripheral Shield I	BATH Al-6061 Hydrogen
39	BATH Peripheral Shield II	BATH Hydrogen
40	BATH Peripheral Shield III	BATH Al-6061 A-286 SS-304 Hydrogen
41	BATH Peripheral Shield IV	BATH Al-6061 Hydrogen
42	Pressure Vessel Side B	Al-7039 Hydrogen

TOR29K/18

Table 3-4. Reactor Weight Model Regions (Cont.)

REGION NUMBER	REGION DESCRIPTION	MATERIAL
43	Lead Central Shield	Lead Alloy Al-6061 Hydrogen
44	Lead Peripheral Shield I	Lead Alloy Al-6061 Hydrogen
45	Lead Peripheral Shield II	Load Alloy Hydrogen
46	Lead Peripheral Shield III	Lead Alloy Hydrogen Al-6061 A-286 SS-304 Hydrogen
47	Lead Peripheral Shield IV	Lead Alloy Al-6061 Hydrogen
48	Peripheral Shield Plate	A-6061 A-286 SS-304 Hydrogen

TOR29K/19

Table 3-4. Reactor Weight Model Regions (Conc.)

REGION NUMBER	REGION DESCRIPTION	MATERIAL
49	Shield Plenum	Al-6061 SS-304 Hydrogen
50	Flow Battle II	Al-6061
51	Central Dome Plenum	Hydrogen
52	Peripheral Dome Plenum	Al-6061 A-286 SS-304 Hydrogen
53	Pressure Vessel Dome	Al-7039
	NERVA Nuclear Subsystem	– – –

TOR29i/20

define the engine specific impulse, propellant flow rate, and required reactor power. The reactor parameters include reactor pressure vessel material, power fractions in the peripheral components, and tie tube power levels.

The user supplies the governing parameters for the fuel elements. These include mean fuel element power, element dimensions, and material. The code modules provides for a choice from three fuel materials: graphitic (UC_2 beads in graphite), composite ((U,Zr)C-Graphite), or carbide ((U,Zr)C). Each fuel type exhibits different properties with regard to mass density, power density, and temperature limits. The fuel to support ratio within the core may be set to one of three patterns: 2:1, 3:1, or 6:1. The fuel parameters are strictly user defined in that the code does not attempt to judge the validity of the inputs. For guidance, Tables 3-1 and 3-2 provide information on typical parameters based on the Rover/NERVA technology.

3.6 Key Assumptions

The code assumes that the same basic design will be used at every size level within the specified code domain. This provides the basis for calculating the size of the core periphery.

The code assumes that the user has specified an attainable combination of input criteria. For example, the code does not verify core criticality and control span. This cannot be accomplished until core neutronics is integrated into the code. Similarly, power distribution in the peripheral regions is based on external data sources such as test measurements.

4.0 SAMPLE NTP ENGINE SYSTEM DESIGN CASE

A NESS NTP engine design problem is presented in this section. A high performance hydrogen ENABLER reactor-based NTP engine system is modeled for the sample design case. Key engine system design parameters are presented in Table 4-1. Key engine system design assumptions are discussed in Ref. 2-3.

Sample case initialized NESS program input sheet are shown in Table 4-2. A clean set of input worksheet forms are given in Appendix A. Table 4-3 presents the NESS VAX mainframe computer input file listing of the sample case. The sample design case output is displayed in Table 4-4.

Table 4-1. Key Sample Case Engine System Design Parameters

Thrust Level	7500. (lbf)
Cycle Type	Expander Cycle
Fuel Type	Composite Fuel
Nozzle Exit Area Ratio	500.
Propellant Used	LH_2
Chamber Pressure	1000. (psia)
Chamber Temperature	4860. (deg R)
Number of Propellant Feed Legs	2

Table 4-2. Sample Case Input Forms

TITLE: LUNAR LH2 NUCLEAR ROCKET		VARIABLE	NAMELIST	UNITS	DEFAULT
Vacuum Thrust (lbf)	75000	FVAC	LIQUID	lbf	75000
Chamber Pressure	1000	PC	INPGEN	psia	500
Propellant: 5) LH2		IPROP	LFLAG		5
Note: GG cycle will use LO2 as needed					
Vehicle Payload wt. (lbm)	Ø	WPAYLD	INPGEN	lbm	0
Miscellaneous Stage wt. (lbm)	Ø	WMISC	INPGEN	lbm	0
Expendable Stage wt. (lbm)	Ø	WEXPND	INPGEN	lbm	0
Cycle Type: 1) Gas Generator 3) Expander		KCYCLE	LFLAG		3
Pump Configuration: 1) Gearbox 2) Single Shaft TPA 3) Twin TPA in series 4) Twin TPA in parallel 5) Multiple feed leg TPA (expander cycle only)		JCNFIG	PUMP		2
Note: If a double run is being made, choose JCNFIG=2 in the input file; the code automatically sets JCNFIG=5 for the second pass.					

DESCRIPTION	ENTRY	VARIABLE	NAMELIST	UNITS	DEFAULT
Boost Pumps: (0 = no, 1 = yes) Oxidizer Fuel		JBPOX JBPFL	PUMP PUMP		0 0
Number of Identical Turbopump Propellant Feed Assemblies (Used if JCNFIG=5 or IDBLRUN=1)	2	NTPA	PUMP		2
Do a double run? (0 = no, 1 = yes) (If yes, first run made at reduced thrust level to size turbomachinery that will be used as part of a multiple-leg feed system used in the second run at full thrust level- available for expander cycle only)	1	IDBLRUN	LFLAG		1
Percent (fraction) of total thrust to be used for the first run (IDBLRUN=1)	0.8	FFRAC	LFLAG		0.8
Input the engine burn time? (0 = no, 1 = yes) (If no, code calculates burn time based on amount of propellant and mass flow rate)	1	IUSRBRN	LIQUID		1
Engine burn time (sec) (IUSRBRN = 1)	3600	TUSRBRN	LIQUID	sec.	3600.0
Percent (fraction) of Non-nuclear weight to be added as margin	0.02	FMARG	LIQUID		0.02
Barrier liquid film length	def	XLFL	LQPERF	in.	1.0
Barrier mixing angle	def	ALFMIX	INJECT	deg.	0.15

		VARIABLE	NAMELIST	UNITS	DEFAULT
Engine Expansion Area Ratio	500	EPS	INPGEN		500
Use a Nozzle Extension? (0 = no, 1 = yes)	1	KEXNOZ	LIQENG		1
Use a 3-portion Nozzle? (regen slots+tubes+extension) (0 = no, 1 = yes)		NOZTYP	LFLAG		1
Nozzle Extension 1 Attach Area Ratio	6	EPSATT	INPGEN		6
Nozzle Extension 2 Attach Area Ratio (NOZTYP = 1)	150	EPSAT2	INPGEN		25
Convergent Nozzle Length (in)	12	XLN	LIQENG	in.	12.
Nozzle Type: (see below)		KNOZ	LIQENG		2
		IPLUG	LIQUID		0
Ratio of Nozzle Length to Minimum Rao Nozzle Length	1.1868	RATMLR	LIQENG		1.177
Gas Generator/Pre-Burner: Mixture Ratio		OFGGPB	PUMP		0.75
Ratio of Specific Heats		GAMGPB	PUMP		1.378
Specific Heat (BTU/lb°R)		CPGGPB	PUMP	BTU/lb °R	2.054
Molecular Weight		WMGGPB	PUMP		3.53

Nozzle Type:

	IPLUG	KNOZ
Conical	0	1
Rao/Bell	0	2
Plug Cluster	1	-
Annular	2	-

		VARIABLE	NAMELIST	UNITS	DEFAULT
Solid Core (ENABLER) Reactor Inputs					
Chamber Temperature	4860	TCHAMBER	REACTR	°R	4860
Fuel Element Channel Diameter	default	DC	REACTR	in.	0.10
Spacing between Holes		SC	REACTR	in.	0.173
Peak to Average Channel Factor		PAC	REACTR		1.2
Number of Holes per Element		HOLES	REACTR		19.0
Fuel Type 1) Graphite 2) Composite 3) Carbide		FTYPE	REACTR		2
Support Pattern 1) 2:1 2) 3:1 3) 6:1		SPAT	REACTR		3
Core Length	52	LC	REACTR	in.	52.
Total Power in each Element	1.2	PMW	REACTR	MW	1.2
Nozzle Flow Percent (fraction) (= Regen flow)	0.7	NFF	REACTR		0.7

Reactor Inputs Cont'd

	VARIABLE	NAMELIST	UNITS	DEFAULT
Heat Pickup per Tie Tube	QIT	REACTR	MW/tube	0.31
Enthalpy of Coolant Entering System	HTANK	REACTR	BTU/lb	-106.0
Fractional Heat Pickup in Reflector	FREF	REACTR		0.0122
Fractional Heat Pickup in External Shield	FES	REACTR		0.00031
Fractional Heat Pickup in Central Shield	FCS	REACTR		0.00173

default

		VARIABLE	NAMELIST	UNITS	DEFAULT
Burned Propellant wt. (lbm)	50000	WTLPRP	LIQUID	lbm	50000
Ullage Fractions					
Oxidizer	def	ULLFOX	LTANK		.02
Fuel	def	ULLFFL	LTANK		.02
Propellant Acquisition Device		KACQOX	LFLAG		6
		KACQFL	LFLAG		6
0) None 1) transverse collapsing AL bladder 2) full bonded rolling diaphram - AL 3) half bonded rolling diaphram - AL 4) full bonded rolling diaphram - stainless steel 5) half bonded rolling diaphram - stainless steel 6) surface tension device					
Propellant Tank Pressurization KGASOX, KGASFL =		KGASOX KGASFL	LFLAG LFLAG		1 1
0) non-autogenous (KGAS=) 1) solid gas generator 2) cold helium		KGAS	LFLAG		2
1) autogenous					
Cold Helium Storage Pressure (psia)	4365	PICG	COLDG	psia	4365
Helium Tank Final Pressure Fraction (less than 1.0 indicates blowdown)	0.8	FPULCG	COLDG		0.8

Description	Input	VARIABLE	NAMELIST	UNITS	DEFAULT
Propellant Tank Heat Transfer 0) ignore heat transfer 1) external boundary exposed to conductive source 2) worst case solar radiation 3) ground hold ice formation		KHXOPT	LFLAG		0
Propellant Tank Insulation (in.)					
Fuel Tank					
SOFI thickness	0.5	TSOFIF	TANKHX	in.	0.5
MLI thickness	0.018	TMLIF	TANKHX	in.	1.97
Oxidizer Tank					
SOFI thickness		TSOFIO	TANKHX	in.	0.5
MLI thickness		TMILO	TANKHX	in.	1.97
Stage Operating Temperature Range (°F)					
Minimum temperature		TMIN	LIQUID	°F	60.0
Nominal temperature	def	TOP	LIQUID	°F	75.0
Maximum temperature		TMAX	LIQUID	°F	90.0

	Input	VARIABLE	NAMELIST	UNITS	DEFAULT
Nozzle Cooling Method (second portion) 2)Regenerative 3)Trans-Regen 4)Radiation 5)Film (GG only) Note: When used, third portion of nozzle extension is automatically radiation cooled		KOOLNZ	LFLAG		2
Nominal Convergent Wall material temperature (°R)	1460	TGWNOM	INREGN	°R	2000.0
Regen/Trans-regen input:					
Output a regen summary (0 = no, 1 = yes)	1	IRPRNT	INREGN		1
Gas wall minimum gauge (in.)	0.01275	GWMING	INREGN	in.	0.025
Gas wall thermal conductivity (BTU/in sec °R)	0.00039	WALLK	INREGN	BTU/in sec °R	0.00039
DIFTBF = ($T_{barrier}$-TGWNOM)/(T_{core}-TGWNOM)	0.05	DIFTBF	INREGN		0.05
Nominal nozzle material temperature (°R)	______	TNENOM	LIQENG	°R	2000.0

	VARIABLE	NAMELIST	UNITS	DEFAULT
Pressure Drop Across Valve (3-30% of Pc)				
Fuel	CPVLVF	LIQUID		0.07
Oxidizer	CPVLVO	LIQUID		0.07
Pressure Drop Across Lines (3-30% of Pc)				
Fuel	CPLINF	LIQUID		0.08
Oxidizer	CPLINO	LIQUID		0.08
Translating Nozzle 0) none 1) spring actuated 2) gas deployed skirt	KTRNOZ	LIQENG		0
Translating Nozzle Attach Area Ratio	EPTRAT	LIQENG		150
Number of Gimballing Engines	NGIMB	LIQUID		1
Gimbal Angle (deg)	GMBANG	LIQUID	deg	6.0

default

def

		VARIABLE	NAMELIST	UNITS	DEFAULT
Engine Materials of Construction (use density and strength at temperature)					
Aluminum 0.098 lb/in3, 25000 psia					
Stainless Steel 0.28 lb/in3, 25000 psia					
Columbium 0.32 lb/in3, 25000 psia					
Silica Phenolic 0.0632 lb/in3, 25000 psia					
Inconel 0.298 lb/in3, 25000 psia					
Copper 0.32 lb/in3, 25000 psia					
Carbon-Carbon 0.061 lb/in3, 50000 psia					
Convergent Nozzle/Throat (regen slots)					
density	0.322	RHCSTR	LIQMAT	lb/in^3	0.28
strength	25000	SIGCHM	LIQMAT	psi	25000.
Regen Closeout material					
density	0.322	RHOCLS	LIQMAT	lb/in^3	0.322
strength	25000	SIGCLS	LIQMAT	psi	25000.
Regen Gas Wall Material Density	0.322	RHOGW	LIQMAT	lb/in^3	0.28
Valve Material Density	0.298	RHOVLV	LIQMAT	lb/in^3	0.098
Nozzle Extension 1 (usually regen tubes)					
density	0.298	RHONZE	LIQMAT	lb/in^3	0.32
strength	25000	SIGNZE	LIQMAT	psi	25000
minimum thickness (in)	0.01	TNZMIN	LIQENG	in.	0.01
Nozzle Extension 2 (NOZTYP=1)					
density	0.061	RHONZ2	LIQMAT	lb/in^3	0.061
strength	50000	SIGNZ2	LIQMAT	psi	50000
minimum thickness	0.1	TNZMN2	LIQENG	in.	0.1

		VARIABLE	NAMELIST	UNITS	DEFAULT
Translating Nozzle Material Density (lb/in^3)		ROTRNZ	LIQMAT	lb/in^3	0.28
Engine Weight Model: -1) input engine weight 1) physical engine weight model		KWTMOD	LFLAG		1
Engine size/weight input (KWTMOD = -1)					
nozzle length (in)		XLNOZ	LIQENG	in.	76.04
engine weight (lb)		WTLTCA	LIQENG	lbm	184.4
nozzle throat diameter (in)		THDUSR	LIQENG	in.	0.0
<u>Regen Cooling:</u>					
Turbine bypass flow fraction	0.71	BYPTUR	INREGN		0.0
Cooling channel multiplier	1.0	CHMULT	INREGN		1.0
Absolute surface roughness of regen channels	def	EPIPE	INREGN	in.	0.00008
Maximum depth to width ratio in cooling channels		HOWMAX	INREGN		5.0
Number of regen segments in:					
Convergent chamber section	def	NCON	INREGN		5
Nozzle		NNZL	INREGN		5

Description	Value	VARIABLE	NAMELIST	UNITS	DEFAULT
Surface area multiplier on regen cooled engine	1.0	SAMULT	INREGN		1.0
Land width of regen cooling channels at throat (in.)	0.04	WLTHR	INREGN	in.	0.03
Channel width of regen cooling channels at throat (in.)	0.1	WTHR	INREGN	in.	0.03
User-defined Regen option:					
Input Regen Delta T and Delta P? (0 = no, 1 = yes)		INDPDT	INREGN		0
Regen jacket total Delta T (INDPDT = 1)		DELTAT	INREGN	°R	100.
Regen jacket total Delta P		DELTAP	INREGN	psia	100.
Tank Outlet Net Positive Suction Pressures					
Oxidizer (psia)		OXNPSP	PUMP	psia	10.
Fuel (psia)	25	FLNPSP	PUMP	psia	10.

Engine Efficiency Adjustment Factors:

		VARIABLE	NAMELIST	UNITS	DEFAULT
Gas Generator Bleed Efficiency Factor in the form: EFFGGB = EFFGGB*ADJGGB		ADJGGB	LQPERF		1.0
The following factors are used in the form: EFF = 1 - (1 - EFF)*adjustment factor					
Boundary Layer Efficiency Adjustment	0.02	ADJBL	LQPERF		1.0
Divergence Efficiency Adjustment	1.0	ADJDIV	LQPERF		1.0
Barrier Cooling Efficiency Adjustment	1.0	ADJMRD	LQPERF		1.0

Weight Multipliers

		VARIABLE	NAMELIST	UNITS	DEFAULT
All Tanks	1.7	CXWTNK CXNCT1-4	CXWMLT NCTINP		1.0 1.0
Fuel Tanks	1.7	CXWFLT	CXWMLT		1.0
Oxidizer Tanks	1.7	CXWOXT	CXWMLT		1.0
Pressure Tanks	1.7	CXWPTN	CXWMLT		1.0
Structure	1.0	CXWSTR	CXWMLT		1.0
Propellant Lines	1.0	CXWATL CXWFTL CXWPTL	CXWMLT CXWMLT CXWMLT		1.0 1.0 1.0
Total Nozzle + Hardware	1.0	CXWENG	CXWMLT		1.0
Valve	2.8	CXVALV	CXWMLT		2.8
Convergent Nozzle	1.0	CXWCHM	CXWMLT		1.0
Nozzle Extension	1.1	CXWNZE	CXWMLT		1.1
Hot Gas Ducts	3.5	CXWDUC	PUMP		3.5
Gimbal System (excl. power supply)	1.4	CXWGIM	CXWMLT		1.4
Thrust Mount	0.9	CXWTHM	CXWMLT		0.9
Gas Generator Injector	1.4	CXWIGG	PUMP		1.4
Turbo Pump Assembly (each component)	1.3	CXWTPA	CXWMLT		1.3

default

Weight Multipliers (cont'd)

Engine Bay Lines 2.5

Support Hardware:

- **Pneumatic Supply System** 0.25
  - NERVA technology, CXWPNEU = 1.0
  - Current technology, CXWPNEU = 0.25
- **Instrumentation** 1.0
- **Reactor Cooldown Assembly (Shutoff and Reactor Cooldown Valve + Line)** 0.9

Ignition System 1.3

default

VARIABLE	NAMELIST	UNITS	DEFAULT
CXWLIN	PUMP		2.5
CXWPNEU	CXWMLT		0.25
CXWINST	CXWMLT		1.0
CXWTNKAS	CXWMLT		0.9
CXWIGN	CXWMLT		1.3

User-Defined Turbomachinery Option

Note: These variables are assigned automatically on the second pass of a double run

	VARIABLE	NAMELIST	UNITS	DEFAULT
Input Turbomachinery Characteristics? (0 = no, 1 = yes)	ISTSET	PUMP		0
Pump Inputs:				
Number of fuel pump stages	PSTAGF	PUMP		1
Number of ox pump stages	PSTAGO	PUMP		1
Fuel pump diameter	PDIAFL	PUMP	in.	0.0
Ox pump diameter	PDIAOX	PUMP	in.	0.0
Fuel boost pump diameter	BPDIAF	PUMP	in.	0.0
Ox boost pump diameter	BPDIAO	PUMP	in.	0.0
Turbine Inputs:				
Choose single shaft or fuel and ox turbines				
Number of turbine stages:				
Single shaft	TSTGES	PUMP		1
Fuel turbine	TSTAGF	PUMP		1
Ox turbine	TSTAGO	PUMP		1
Turbine Diameter:				
Single shaft	TDIAM	PUMP	in.	0.0
Fuel turbine	TDIAFL	PUMP	in.	0.0
Ox turbine	TDIAOX	PUMP	in.	0.0

User-Defined Turbomachinery (cont'd)

		VARIABLE	NAMELIST	UNITS	DEFAULT
Turbine Admission Fraction:					
Single shaft		ADMFR	PUMP		1.0
Fuel turbine		ADMFRF	PUMP		1.0
Ox turbine		ADMFRO	PUMP		1.0
Turbine Annulus Area:					
Single shaft		ANAREA	PUMP	in^2	0.0
Fuel turbine		ANARFL	PUMP	in^2	0.0
Ox turbine		ANAROX	PUMP	in^2	0.0
Input Turbopump Assembly Weights? (0 = no, 1 = yes)	______	INPTPA	PUMP		0
Total TPA Weight	______	TPAWT	PUMP	lbm	0.0
TPA Start System Weight	______	WSTART	PUMP	lbm	0.0
Ignition System Weight	______	WIGNIT	PUMP	lbm	0.0
Hot Gas Manifold Weight	______	WHGMF	PUMP	lbm	0.0
Gearbox Weight	______	WGBOX	PUMP	lbm	0.0
Autogenous Heat Exchanger Weight	______	WTHTX	PUMP	lbm	0.0
Gas Generator/Preburner Weight	______	WGGPB	PUMP	lbm	0.0

User-Defined Turbomachinery (cont'd)

		VARIABLE	NAMELIST	UNITS	DEFAULT
Have User-Defined Gas Generator? (0 = no, 1 = yes)	______	IUSRGG	PUMP		0
Gas Generator Inputs: Bleed Nozzle Flowrate	______	WDBLNZ	PUMP	lb/sec	0.1
GG Bleed Efficiency	______	ETAGGB	PUMP		0.99
Max Turbine Temp. Limit	______	TTLIMT	PUMP	°R	5000.
Turbine/GG Inlet Temp.	______	TUSRGG	PUMP	°R	0.0
Turbine Flowrate	______	WDUSRG	PUMP	lb/sec	0.0
Isp of GG Bleed	______	USRGGI	PUMP	sec	0.0
Turbine Inlet Pressure	______	PUSRTI	PUMP	psia	0.0
User Defined Drive Fluid Weight	______	WPUSRG	PUMP	lbm	10.0
User Defined Drive Fluid Tank Weight	______	WIUSRG	PUMP	lbm	10.0
Density of Drive Fluid	______	ROUSRG	PUMP	lb/in^3	0.01
Yield Stress of Drive Fluid Tank	______	SYUSRG	PUMP	psi	25000.0
Density of Drive Fluid Tank Material	______	ROUSMT	PUMP	lb/in^3	0.098

DESCRIPTION	VARIABLE	NAMELIST	UNITS	DEFAULT
Transpiration Cooling Inputs:				
Transpiration Cooling Criteria	IDTRAN	INREGN		2
1) use QMAXTR				
2) input EPSTRD and EPSTRU				
Maximum heat flux before transpiration cooling (BTU/in^2 sec)	QMAXTR	INREGN	BTU/in^2 s	1.0
Upstream area ratio for transp. cooling	EPSTRU	INREGN		2.0
Downstream area ratio for transp. cooling	EPSTRD	INREGN		1.2
Transpiration section platelet dimensions				
etched platelet thickness	TGEOH	INREGN	in.	0.08
platelet land thickness	TGEOL	INREGN	in.	0.1
separator platelet thickness	TGEOS	INREGN	in.	0.04
flow passage widths	TGEOW	INREGN	in.	0.14
Transpiration cooling insert:				
material density	RHTRIN	LIQMAT	lb/in3	0.28
thickness	TRINST	LIQMAT	in.	0.3
thermal conductivity (BTU/in sec °R)	TRANKM	INREGN	BTU/in s °R	0.0004

Tank Geometry

	VARIABLE	NAMELIST	UNITS	DEFAULT
Tandem Tanks	NCTNK	LFLAG	-	0
raw Sketch Here) monocoque tanks (1) suspended tanks (0)	MNCQA	TNKGEO	-	1
separate domes (0)	MNCQF	TNKGEO	-	1
common domes (1)	KDOME	TNKGEO	-	1
Pressure Tank Geometry 0) spherical in engine bay	KPRESS	TNKGEO	-	0
number of tanks	NPRB	TNKGEO	-	1
1) suspended forward of forward tank 2) monocoque separate dome 3) monocoque common dome 4) cylindrical in forward tank				
propellant tank head ellipse ratio [1.38]	ELDOME	INPGEN	-	1.0
pressurant tank head ellipse ratio [ ]	ELRP	LTANK	-	1.0
propellant tank dome orientation (-1 = convex forward) (1 = convex aft	KXATAH	TNKGEO	-	1
	KXATFH	TNKGEO	-	-1
	KXFTAH	TNKGEO	-	-1
	KXFTFH	TNKGEO	-	-1
	KPRPA	TNKGEO	-	2
propellant location (1 = fuel aft, not 1 = fuel not aft				

Non-Conventional Tanks

(Draw Sketch Here)

	VARIABLE	NAMELIST	UNITS	DEFAULT
Total number of tanks	NTANKS	NCTINP	-	3
Tank ellipse ratios	ELTNK1-4	NCTINP	-	1.0
Tank types (1 = CSE, 2 = torus)	KTANK1-4	NCTINP	-	1
Tank contents (1 = ox, 2 = fuel, 3 = press)	INTNK1-4	NCTINP	-	1
Tank angular location (deg)	TANGL1-4	NCTINP	deg	0.0
Tank radial location	RADLO1-4	NCTINP	-	0.0
Kind of dimensional input				
dimensionless (0)	KALMOD	NCTINP	-	0
L_{cyl}/D ; R_{hub}/R_{tube}	RDIM1-4	NCTINP	-	2.0
major dimension (in) (1) R_{tank} ; R_{hub}	RMAJ1-4	NCTINP	in	25.0
Engine angular location (deg)	ENGAN1-4	NCTINP	deg	0.0
Engine radial location	ENGRD1-4	NCTINP	-	0.0
Stage Diamater (in)	DMOTOR	INPGEN	in	66.0
Forward Skirt Length (in)	FFSKTL	LIQUID	-	0.3
Aft Skirt Length (in)	FASKTL	LIQUID	-	0.067

. of Construction
(1..1 in material ID#)

1-10) user defined
11) 6061-T6 aluminum @ 300°F
12) 6Al-4V titanium @ 300°F
13) aged 6Al-4V @ 300°F
14) cryoformed 301 CRES @ 500°F
15) aged 301 CRES @ 500°F

Fuel Tank	11
Oxidizer Tank	
Pressurant Tank	
Structure and Skirts	11

Design Safety Factors

Fuel Tank	
Oxidizer Tank	
Pressure Tank	
Structure and Skirts	
lines	

default

VARIABLE	NAMELIST	UNITS	DEFAULT
MTNKFL	LIQMAT	-	1
MTNKOX	LIQMAT	-	1
MATPT	LIQMAT	-	2
MATSTR	LIQMAT	-	1
MATNK1-4	NCTINP	-	1
RHO	LIQMAT	lb/in^3	-
YMOD	LIQMAT	psi	-
SIGMAX	LIQMAT	psi	-
SPHEAT	LIQMAT	BTU/lb °R	-
CONDCT	LIQMAT	BTU/in sec°R	-
THING	LIQMAT	in	0.035
THINGS	LIQMAT	in	0.035
SFFLTK	LIQMAT	-	1.25
SFOXTK	LIQMAT	-	1.25
SFPRTK	LIQMAT	-	1.5
SFSTRC	LIQMAT	-	1.25
SFLINE	LIQMAT	-	2.0
SFTNK1-4	NCTINP	-	1.5

Engine Mounting Length Adjustment (in)

Propellant Expulsion Efficiency

0) calculate

1) input

Fuel expulsion efficiency

Oxidizer expulsion efficiency

VARIABLE	NAMELIST	UNITS	DEFAULT
XMOUNT	LIQENG	in	2.0
INPEXF	LFLAG	-	0
INPEXO	LFLAG	-	0
EXPLFL	LTANK	-	0.995
EXPLOX	LTANK	-	0.995

Tankage

Line printer characters per inch

Horizontal

Vertical

Propellant Acquisition device material density ($lb/in.^3$)

fuel tank (KACQFL = 6)

ox tank (KACQOX = 6)

default

Cross sectional area of shroud stiffening rings ($in.^2$)

forward shroud

aft shroud

VARIABLE	NAMELIST	UNITS	DEFAULT
CHRPIX	NCTINP	char/in.	10
CHRPIY	NCTINP	char/in.	6
DACQFL	LTANK	$lb/in.^3$	0.1
DACQOX	LTANK	$lb/in.^3$	0.1
AESSR	LTANK	in^2	0.152
AFSSR	LTANK	in^2	0.25

Figur (cont.) ray

	VARIABLE	NAMELIST	UNITS	DEFAULT
General Input				
Propellant temperatures input option for library propellants (IPROP > 0) (Circle One) 0) use default temperatures 1) input temperatures	IPUTMP	LFLAG	-	0
minimum fuel temperature (°R) [ ]	TPMINF	LFUEL	°R	varies
nominal fuel temperature (°R) [ ]	TPNOMF	LFUEL	°R	varies
maximum fuel temperature (°R) [ ]	TPMAXF	LFUEL	°R	varies
minimum ox temperature (°R) [ ]	TPMINO	LOXID	°R	varies
nominal ox temperature (°R) [ ]	TPNOMO	LOXID	°R	varies
maximum ox temperature (°R) [ ]	TPMAXO	LOXID	°R	varies

General Input

Input	VARIABLE	NAMELIST	UNITS	DEFAULT
Lines full at burnout (Circle One) (0 = No, 1 = Yes)	LNFULL	LFLAG	-	1
Miscellaneous on-board propellant (lbm) (remains on stage at burnout) fuel [ ]	WMISFL	INPGEN	lbm	0.0
ox [ ]	WMISOX	INPGEN	lbm	0.0
Number of iterations on temperature schedule [2] (a value of 1 performs temperature schedule calculations only once)	NTMPIT	LIQUID	-	1

Figure 2.3 Contingent Input Worksheet

Tandem Tanks (NCTNK = 0)

Space between suspended tank and structural vehicle wall

aft tank (MNCQA = 0)

forward tank (MNCQF = 0)

pressure tank (KPRESS = 1)

Pressure tank insulation density [ ]

(NCTNK = 0)(lb/in.^{3})

default

Propellant feed line flag (Circle One)

0) external feed line

1) internal feed line

Number of pressure bottles in engine bay [ ]

(KPRESS = 0)

VARIABLE	NAMELIST	UNITS	DEFAULT
TSPCA	LTANK	in.	0.0
TSPCF	LTANK	in.	0.0
TSPCP	LTANK	in.	0.0
RHOINS	MATER	lb/in.^{3}	.0414
KLINEA	TNKGEO	-	1
NPRB	TNKGEO	-	1

Figure 2.5. (cont.)

<u>Tandem Tanks</u> (NCTNK = 0)

defaults

Description	VARIABLE	NAMELIST	UNITS	DEFAULT
Stage critical bending moment (NCTNK = 0) (in./lb_f)	CBM	LTANK	in./lb_f	0.0
Maximum carry moment (NCTNK = 0)(in./lb_f)	CMMAX	LTANK	in./lb_f	0.0
Space between aft and forward tank (KDOME = 0) (in.)	CLRAF	LTANK	in.	0.0
Space between forward tank and pressure tank (KPRESS = 1-3) (in.)	CLRFP	LTANK	in.	0.0
Density of pressure tank insulation (lb/m^3)	RHPTIN	LIQMAT	lb/m^3	0.04
Insulation thickness for pressure tank (in.)	TINSUL	LIQMAT	in.	0.0

Figure (cont.)

Non-Conventional Tanks (NCTNK = 1)

Non-conventional tank usable volume ratios

fuel tanks

ox tanks

pressure tanks

Minimum clearance between non-conventional tanks (in.)

Minimum clearnace between nozzles in non-conventional model (in.)

Non-conventional models engine nesting mode (Circle One)

1) nest each engine independently

2) nest engines to highest common plane

3) nest engine exit plane to end of tankage + XMOUNT

Non-conventional tankage thickness option (Circle One)

0) variable wall thickness

1) constant wall thickness

VARIABLE	NAMELIST	UNITS	DEFAULT
RATNK1-4	NCTINP	-	1.0
CLRTNK	NCTINP	in.	2.0
ENGSPC	NCTINP	in.	2.0
KNEST	NCTINP	-	3
KTHCK1-4	NCTINP	-	1

Figui - . (cont.)

Non-Conventional Tanks (NCTNK = 1)

	VARIABLE	NAMELIST	UNITS	DEFAULT
Non-conventional tank feed line hydraulics				
velocity heads lost in fuel lines including valves, bends, etc.	FLKFCT	LTANK	-	5.0
velocity heads lost in ox lines including valves, bends, etc.	OXKFCT	LTANK	-	5.0
absolute surface roughness of fuel lines (in.)	RUFFFL	LTANK	in.	.0001
absolute surface roughness of ox lines (in.)	RUFFOX	LTANK	in.	.0001

Cold Gas Pressurization

Pressurant Properties (default is Helium)

default

Description	Input	VARIABLE	NAMELIST	UNITS	DEFAULT
Isentropic ratio of specific heats (-)		GAMICG	COLDG	-	1.66
Polytropic ratio of specific heat at time equal infinity (-)		GAMPCG	COLDG	-	1.0
Time at which polytropic ratio falls to 1.1 (sec.)		TIMPCG	COLDG	-	240
Molecular wt. of pressurant (lb/lbmole)		WTMCG	COLDG	lb/lbmole	4.0

Solid gas generator pressurization (default is TAL-8)

Description		VARIABLE	NAMELIST	UNITS	DEFAULT
Minimum port to throat area ratio		APATGG	SOLDGG	-	3.0
Ratio of equilibrium temperature in propellant tank to minimum operating temperature (TMIN)		BTEQGG	SOLDGG	-	1.5
Burn rate coefficient of solid grain (in./sec.)		CBRGG	SOLDGG	in./sec.	0.095
Design complexity multiplier solid g.g.		CDESGG	SOLDGG	-	1.25
Solid grain characteristic velocity (ft./sec.)		CSGG	SOLDGG	ft./sec.	3932
Minimum allowable solid grain diameter (in.)		DMINSG	SOLDGG	in.	3.0
Burn rate exponent of solid grain		EBRGG	SOLDGG	-	0.64
Molar fraction of water in combustion products		FH2OGG	SOLDGG	-	0.2662
Multiplying factor on ullage pressure to calculate minimum operating g.g. pressure		FPULGG	SOLDGG	-	1.1
Combustion products ratio of specific heats		GAMGG	SOLDGG	-	1.27
Temperature sensitivity of g.g. pressure (1/°R)		PIPKGG	SOLDGG	1/°R	0.0036
Solid grain density (lb/in.^{3})		RHOGG	SOLDGG	lb/in.^{3}	0.056

Figu .   (cont.)

Solid gas generator pressurization

Description	Input	VARIABLE	NAMELIST	UNITS	DEFAULT
Burn rate temperature sensitivity of solid grain (1/°R)		SIGGG	SOLDGG	1/°R	0.0013
Gas generator combustion temperature (°R)		TCMBGG	SOLDGG	°R	2130
Temperature decay time constant		TDCYGG	SOLDGG	sec.	100
Reference temperature for burn rate coefficient (°R)		TREFGG	SOLDGG	°F	80
Molecular weight of combustion products		WTMGG	SOLDGG	lb/lbmole	19.0

	VARIABLE	NAMELIST	UNITS	DEFAULT
Pump				
Boost pump fraction of total propellant head rise				
fuel [ ]	BPFRFL	PUMP	-	.0464
ox [ ]	BPFROX	PUMP	-	.0464
Gas generator/pre-burner control valve pressure drop multiplier [ ]	CVMLTF	PUMP	-	0.65
Pressure ratio across gas generator/pre-burner				
fuel side [ ]	PBPRF	PUMP	-	1.2
ox side [ ]	PBPRO	PUMP	-	1.2
Turbine outlet pressure (for gas generator bleed cycle) (KCYCLE = 1) (psia) [ ]	PTURBO	PUMP	psia	20.
Number of turbo pump assemblies (Circle One)				
1) 1 TPA per stage				
2) 1 or more TPA per engine	KPUMP	PUMP	-	2
Autogenous Pressurant temperature (°R)				
fuel [100] (KGASFL = 1)	TULLFL	PUMP	°R	800
ox [250] (KGASOX = 1)	TULLOX	PUMP	°R	800

default

Figure 4.3. (cont.)

<u>Pump</u>

default

Description	VARIABLE	NAMELIST	UNITS	DEFAULT
Suction specific speeds of propellant pumps				
main fuel pump	SSSFL	PUMP	-	20000
main ox pump	SSSOX	PUMP	-	20000
fuel boost pump	SSSBPF	PUMP	-	30000
ox boost pump	SSSBPO	PUMP	-	30000
Initial value of turbine pressure ratio (KCYCLE > = 2)	TURBPR	PUMP	-	2.0
Turbine pitch line velocity divided by isentropic spouting velocity	UOVERC	PUMP	-	0.4
Area ratio of bleed nozzle (KCYCLE = 1)	EPSGGB	PUMP	-	2.0
Gas generator or pre-burner contraction ratio	GGCR	PUMP	-	12.
Gas generator or pre-burner injector material density (lb/m^3)	ROINGG	PUMP	$lb/in.^3$	0.3
Gas generator or pre-burner injector yield strength (psi)	SYINGG	PUMP	psi	30000
Hot gas duct material density ($lb/in.^3$)	ROSTAK	PUMP	$lb/in.^3$	0.3
Hot gas duct material yield strength (psi)	SYDUCT	PUMP	psi	30000

Figur. (cont.)

Pump

TPA Start System design (Circle One)

0) tank head
1) cold gas spin
2) start tanks
3) solid cartridge

Description	Input	VARIABLE	NAMELIST	UNITS	DEFAULT
TPA Start System design		ISTART	PUMP	-	0
TPA Start System					
start valve complexity multiplier		CV	PUMP	-	1.0
accumulator valve complexity multiplier (ISTART = 2)		CVACUM	PUMP	-	1.0
solid grain burn rate (ISTART = 3) (in./sec.)		BURNRA	PUMP	in./sec.	0.14
molecular weight of pressurization gas (ISTART = 2)		GASMW	PUMP	lb/lbmole	28.
number of engine restarts		NR	PUMP	-	1
start bottle material density (ISTART = 2) (lb/in.^{3})		RHOBOT	PUMP	lb/in.^{3}	0.16
start cylinder material density (ISTART = 2) (lb/in.^{3})		RHOCYL	PUMP	lb/in.^{3}	3.3
start sphere material density (ISTART = 1) (lb/in.^{3})		RHOSPH	PUMP	lb/in.^{3}	0.1
start cartridge material density (ISTART = 3) (lb/in.^{3})		ROCART	PUMP	lb/in.^{3}	0.3
start cartridge grain density (ISTART = 3) (lb/in.^{3})		ROGRAN	PUMP	lb/in.^{3}	0.07
start bottle yield strength (ISTART = 2) (psi)		SYBOT	PUMP	psi	75000
start cartridge yield strength (ISTART = 3) (psi)		SYCART	PUMP	psi	100000
start cylinder yield strength (ISTART = 2) (psi)		SYCYL	PUMP	psi	30000
start system sphere yield strength (ISTART = 1) (psi)		SYSPH	PUMP	psi	47000
start bottle gas temperature (ISTART = 2) (°R)		TBOGAS	PUMP	°R	530
start system sphere temperature (ISTART = 1) (°R)		TSPH	PUMP	°R	210

Figur... (cont.)

Pump

TPA Material properties

Description	Input	VARIABLE	NAMELIST	UNITS	DEFAULT
fuel turbine blade material density (JCNFIG = 3 or 4) ($lb/in.^3$)		RHOTFL	PUMP	$lb/in.^3$	0.3
ox turbine blade material density (JCNFIG = 3 or 4) ($lb/in.^3$)		RHOTOX	PUMP	$lb/in.^3$	0.3
turbine blade material density (JCNFIG = 1 or 2) ($lb/in.^3$)	0.305	RHOTUR	PUMP	$lb/in.^3$	0.3
TPA effective material density ($lb/in.^3$)	0.298	RHOTPA	PUMP	$lb/in.^3$	0.3
Turbine blade ultimate strength (psi)	134000	US	PUMP	psi	127000
Turbine blade yield strength (psi)	120000	YS	PUMP	psi	104000
Propellant line material density (enginebay) ($lb/in.^3$)	0.298	ROLINE	PUMP	$lb/in.^3$	0.3
Propellant line material yield strength (psi)		SYLIN	PUMP	psi	30000
Cold gas valve material density (ISTART = 1)		ROSPVL	PUMP	$lb/in.^3$	0.3
Accumulator valve material density (ISTART = 2)		ROACVL	PUMP	$lb/in.^3$	0.3

Tank Heat Transfer

Tank insulation conductivity flag (Circle One)

0) Input conductivity of MLI and SOFI

1) calculate conductivity of MLI and SOFI

Effective thermal conductivity of MLI (BTU/in.sec.°R) [ ]

Effective thermal conductivity of SOFI (BTU/in.sec.°R) [ ]

SOFI Thermal conductivity constants (KALCON = 1)

$K = A + B * T$

A (BTU/in.sec.°R) [ ]

B (BTU/in.sec.°R^2) [ ]

Insulation density (lb/in.^{3})

MLI [ ]

SOFI [ ]

default

Radiation shields per inch in MLI (#/in.) [ ]

Average stage acceleration (g's) [ ]

Iteration counter in heat transfer calcs [ ]

VARIABLE	NAMELIST	UNITS	DEFAULT
KALCON	TANKHX	-	1
CNMLI	TANKHX	BTU/in.sec°R	4.0E-9
CNSOFI	TANKHX	BTU/in.sec°R	3.5E-7
SOFIA	TANKHX	BTU/in.sec°R	3.935E-8
SOFIB	TANKHX	BTU/in.sec°R^2	5.676E-10
DNMLI	TANKHX	lb/in.^{3}	.002
DNSOFI	TANKHX	lb/in.^{3}	.00127
RADPIN	TANKHX	#/in.	40.
SACCEL	TANKHX	g's	2.0
NITHX	TANKHX	-	8

Tank Heat Transfer

		VARIABLE	NAMELIST	UNITS	DEFAULT
Fraction of propellant tank nominal ullage pressure at which venting occurs					
fuel	def	FVENTF	TANKHX	-	1.1
ox	def	FVENTO	TANKHX	-	1.1
Stage action time (sec.)	259200	FLTTIM	TANKHX	sec.	100
Stage hold time (sec.)	0	HLDTIM	TANKHX	sec.	100
MLI environment flag (Circle One)	4	MLIENV	TANKHX	-	1
MLI purge gas pressure at space hold conditions (psia)	def	PRGMLI	TANKHX	psia	2.0E-7

MLI environment flag (Circle One)

1) Ground hold with N_2 purge
2) Ground hold with He purge
3) Space hold with N_2 purge depleted to PRGMLI psia
4) Space hold with He purge depleted to PRGMLI psia

Figur. . (cont.)

Tank Heat Transfer

External tank boundary temperature (KHXOPT = 1) (°R) [ ]

Space hold heat transfer (KHXOPT = 2)

Earth Infrared heat flux (BTU/sec.in.^{2}) [ ]

Earth reflectance (albedo) [ ]

Average orbital altitude (miles) [ ]

Angle between earth-sun vector and vehicle orbital plane (deg) [ ]

Stage absorbativity [ ]

Solar heat flux (BTU/sec.in.^{2}) [ ]

default

Ground Hold Ice formation (KHXOPT = 3)

Relative humidity [ ]

Ambient temperature (°R) [ ]

Wind velocity (MPH) [ ]

VARIABLE	NAMELIST	UNITS	DEFAULT
TEXBOU	TANKHX	°R	560
EARIR	TANKHX	BTU/sec.in.^{2}	1.35E-4
EARREF	TANKHX	-	0.39
HXALT	TANKHX	miles	125
ORBANG	TANKHX	deg	0.0
SABSOR	TANKHX	-	0.2
SOLCON	TANKHX	BTU/sec.in.^{2}	8.28E-4
RELHUM	TANKHX	-	50.
TAMICE	TANKHX	°R	560.
WNDMPH	TANKHX	mph	10.

Figure (cont.)

<u>Positive Expulsion Bladders</u>

		VARIABLE	NAMELIST	UNITS	DEFAULT
Space between transverse collapsing bladder and tank wall (in.)					
ox tank	☐	BLSPOX	BLADER	in.	.01
fuel tank	☐	BLSPFL	BLADER	in.	.01
Bond material density of bonded rolling diaphram					
ox tank	☐ (lb/in.^{3})	DBNDOX	BLADER	lb/in.^{3}	.04
fuel tank	☐	DBNDFL	BLADER	lb/in.^{3}	.04
Bladder thickness (for BRD only) (in.)					
ox tank	☐	TBLDOX	BLADER	in.	.025
fuel tank	☐	TBLDFL	BLADER	in.	.025
Bond thickness (for BRD only) (in.)					
ox tank	☐				
fuel tank	☐				

default

Table 4-3. Sample Case Input File Listing

```
 LUNAR LH2 NUCLEAR ROCKET
C
C ****************************************************************
C
C  System Summary: This file is for the Nuclear (Liquid Hydrogen)
C  propulsion system for the Lunar Vehicle.
C
C ****************************************************************
C
$INPOPT
 INDES  = 1,
 IOPF   = 0,
 IPLOT  = 0,
 IPRINT = 1,2,2,2,1,
 IOPT   = 92,42,
 IERRMD = 0,
 IOBJF  = 13,
 OBJSCL = 1.0,
 TLIMIT = 900.,
$END
$NLP
$END
$INPGEN
 EPS    = 500.0,
 EPSATT = 6.0,
 EPSAT2 = 150.,
 PC     = 1000.0,
 WPAYLD = 0.,
 DMOTOR = 100.,
 ELDOME = 1.38,
$END
$INTSTG
$END
$NOZZLE
$END
$MATER
$END
$FILMNT
$END
$PROPEL
$END
$INTRAJ
$END
$GUIDA
$END
$AEROD
$END
$THVST
$END
$ORB
$END
$LIQUID
 NGIMB  = 1,
 GMBANG = 6.,
 NTMPIT = 2,
 CPVLVF = 0.07,
 CPLINF = 0.08,
 FFSKTL = 1.0,
 FASKTL = 1.0,
 FVAC   = 75000.0,
```

```
  WTLPRP = 8000.,
  IUSRBRN= 1,
  TUSRBRN= 3600.,
  FMARG  = 0.02,
 $END
 $LFLAG
  IDBLRUN=1,
  FFRAC  = 0.8,
  NOZTYP = 1,
  KPERF = 1,
  KHXOPT = 2,
  KWTMOD = 1,
  KOOLNZ = 2,
  KACQFL = 6,
  KGASFL = 0,
  IPROP  = 5,
C
C  Expander Cycle (Fuel Cooled)
C
  KCYCLE = 3,
 $END
 $LTANK
 $END
 $TNKGEO
  KLINEA = 0,
  KPRPA = 0,
  KDOME = 0,
 $END
 $BLADER
 $END
 $COLDG
 $END
 $SOLDGG
 $END
 $PUMP
  RHOTPA = 0.298,
  ROLINE = 0.298,
  RHOTUR = 0.305,
  US     = 134000.,
  YS     = 120000.,
C  *****CENTAUR
  TULLFL = 100.0,
C *************
  SSSMAX  = 20000.0,
  SSSFL  = 20000.0,
  SSSBPF = 20000.0,
  TURBPR = 1.3,
  ROSTAK = 0.298,
  FLNPSP = 25.,
  PBPRF = 1.2,
  BPFRFL = 0.0,
  KPUMP = 2,
  JCNFIG = 2,
  NTPA   = 2,
C
C   Boost Pumps
C
  JBPFL  = 0,
  JBPOX  = 0,
  NR     = 60,
```

```
  CXWLIN = 2.5,
 $END
 $INJECT
 $END
 $LIQENG
  KTRNOZ = 0,
  KEXNOZ = 1,
  TNZMIN = 0.010,
  TNZMN2 = 0.1,
  SFCHM  = 1.25,
  XLN    = 12.0,
  RATMLR = 1.1868,
 $END
 $INREGN
C  ********************
  INDPDT = 0,
C   ********************
  BYPTUR = 0.71,
  HOWMAX = 3.2,
  SAMULT = 1.0,
  CHMULT = 1.0,
  WLTHR  = 0.04,
  WTHR   = 0.1,
  TGWNOM = 1460.0,
  IRPRNT = 1,
  NNZL = 5,
  NCON = 5,
  GWMING = 0.01275,
  WALLK = .00039,
  DIFTBF = 0.05,
 $END
 $ABLATE
 $END
 $LIQMAT
  RHCSTR = 0.322,
  RHOGW  = 0.322,
  RHOCLS = 0.322,
  RHONZE = 0.298,
  RHONZ2 = 0.061,
  MTNKFL = 11,
  MATSTR = 11,
  RHOINJ = 0.298,
  RHOVLV = 0.298,
  SIGNZE = 37000.0,
 $END
 $CXWMLT
  CXWENG = 1.0,
  CXWTPA = 1.3,
  CXWTNK = 1.7,
  CXWFLT = 1.7,
  CXWOXT = 1.7,
  CXWCHM = 1.0,
  CXWGIM = 1.4,
  CXWPNEU= 0.25,
  CXWINST= 1.0,
  CXWTNKAS=0.9,
  CXWTHM = 0.9,
  CXWIGN = 1.3,
 $END
 $LPROP
```


C-2

```
$END
$LQPERF
 OFCORE = 0.0,
 ADJBL = 0.2,
$END
$THROT
$END
$LFUEL
$END
$LOXID
$END
$NCTINP
$END
$TANKHX
 FLTTIM = 259200.,
 HLDTIM = 0.,
 MLIENV = 4,
 HXALT  = 250.0,
 TSOFIF = 0.5,
 TMLIF  = 0.018,
$END
$REACTR
 TCHAMBER=4860.,
$END
```

Table 4-4. Sample Case Output

LUNAR LH2 NUCLEAR ROCKET

KEY INPUTS

THRUST LEVEL =	75000. (lbf)
CYCLE TYPE =	EXPANDER CYCLE
FUEL TYPE =	COMPOSITE FUEL
NOZZLE EXIT AREA RATIO =	500.
PROPELLANT USED =	LH2
CHAMBER PRESSURE =	1000. (psia)
CHAMBER TEMPERATURE =	4860. (deg R)
NUMBER OF PROPELLANT FEED LEGS =	2

```
                  OUTPUT FOR MULTIPLE PUMPS AT FULL THRUST LEVEL

PROPELLANT COMBINATION FOR STAGE  1 IS THE FOLLOWING

     PROPELLANTS  LIQUID OXYGEN - LIQUID HYDROGEN
     ASSUMPTIONS:
                  TEMP      ENTHALPY
              LOX  90.18 K  -3093. CAL/MOL
              LH2  20.27 K  -2154. CAL/MOL

         ODK VALUES CORRESPOND TO THROAT RADIUS=2.289 IN.
          C-STAR & CHAMBER TEMP DATA EVALUATED AT ODE PC & ODE MR VALUES



 SIZE OF VARIOUS DATA ARRAYS
TURBINE PRESSURE RATIO=    1.694885207927133
TURBINE PRESSURE RATIO=    1.795103784319999
SUCCESSFUL CYCLE POWER BALANCE
TURBINE PRESSURE RATIO=    1.795103784319999
VENT PRESSURE IS SUPERCRITICAL IN FUEL TANK
```

```
TANKAGE SUMMARY FOR STAGE #1
      EXPANDER CYCLE (FUEL SIDE)
      AFT TANK CONTAINS OXIDIZER ... FORWARD TANK CONTAINS FUEL
      FUEL TANK IS PRESSURIZED WITH COLD GAS
      OXIDIZER TANK IS PRESSURIZED WITH COLD GAS
      TANK MATERIALS  (OX - aluminum )  (FUEL - aluminum )  (PRESSURANT - USER DEF )
```

.. DIMENSIONS (INCHES) ...

STAGE DIAMETER	100.00
TOTAL STAGE LENGTH	889.06
TOTAL TANK LENGTH	494.15
NOZZLE LENGTH	328.91
CONVERGENT NOZZLE LENGTH	12.00
INJECTOR FACE FORWARD LENGTH	0.00
MOUNT LENGTH	2.00
TANK HEAD ELLIPSE RATIO	1.38
PRESSURE TANK ELLIPSE RATIO	1.00
AFT TANK HEAD HEIGHT	36.04
FORWARD TANK HEAD HEIGHT	36.04
PRESSURE TANK HEAD HEIGHT	46.17
PRESSURE TANK DIAMETER	92.35
AFT TANK CYLINDRICAL LENGTH	0.00
FORWARD TANK CYLINDRICAL LENGTH	419.99
PRESSURE TANK CYLINDRICAL LNGTH	0.00
AFT LINE DIAMETER	0.00
FORWARD LINE DIAMETER	2.40
AFT SKIRT LENGTH	378.96
FORWARD SKIRT LENGTH	36.04
STRUCTURAL WALL THICKNESS	0.090
AFT TANK WALL THICKNESS	0.030
FORWARD TANK WALL THICKNESS	0.194
PRESSURE TANK WALL THICKNESS	1.134
AFT TANK DOME THICKNESS	0.030
FORWARD TANK DOME THICKNESS	0.134
PRESSURE TANK DOME THICKNESS	1.134
FUEL TANK MLI THICKNESS	0.02
FUEL TANK SOFI THICKNESS	0.50
OXIDIZER TANK MLI THICKNESS	0.02
OXIDIZER TANK SOFI THICKNESS	0.50
PRESSURE TANK INSULATION THICK	0.00
FUEL TNK HEAT FLUX(BTU/HR IN**2)	0.08
OX TANK HEAT FLUX(BTU/HR IN**2)	0.00
FUEL BOILOFF RATE (LB/SEC)	0.000
OX BOILOFF RATE (LB/SEC)	0.000

... WEIGHTS (POUNDS) ...

AFT TANK	27.58
FORWARD TANK	4897.58
PRESSURE TANK	8063.91
TANK CONSTRUCTION WEIGHT	9092.35
STRUCTURAL WALL	5.73
AFT SKIRT	354.59
FORWARD SKIRT	107.30
TANK MOUNT	0.00
PRESSURE TANK INSULATION	0.00
FUEL TANK INSULATION	237.41
OXIDIZER TANK INSULATION	60.79
REVERSE HEAD STIFFENER	268.33
FUEL ACQUISITION SYSTEM	11.28
OXIDIZER ACQUISITION SYSTEM	0.00
PRESSURANT CONTROL HARDWARE	57.13
TANK LINES	21.42
BURNED FUEL	8000.00
BURNED OXIDIZER	0.00
FUEL RESIDUAL	8.06
OXIDIZER RESIDUAL	0.00
STORED PRESSURANT	574.96
HOLD TIME FUEL BOILOFF	0.00
HOLD TIME OX BOILOFF	0.00
FLIGHT FUEL BOILOFF	0.00
FLIGHT OXIDIZER BOILOFF	0.00
MISC EXPENDED FUEL	0.00
MISC EXPENDED OXIDIZER	0.00
MISCELLANEOUS WEIGHT	0.00
INTERSTAGE WEIGHT	0.00

... INPUT MINIMUM SAFETY FACTORS ...

STRUCTURAL WALL	1.25
LINES	2.00
OXIDIZER TANK	1.25
FUEL TANK	1.25
PRESSURE TANK	1.50

```
                PROPELLANT SUMMARY FOR STAGE #1
                     PROPELLANT IS LH2

                                          NOMINAL PROPELLANT BULK DENSITY(LB/IN**3)=    0.0025

.. OXIDIZER ...                                              ... FUEL ...

       NOMINAL TANK PRESSURE(PSIA)          0.0                     NOMINAL TANK PRESSURE(PSIA)          140.8

       NOMINAL PROPELLANT TEMP(DEGR)        0.0                     NOMINAL PROPELLANT TEMP(DEGR)         40.0
       NOMINAL DENSITY(LB/IN**3)            0.0000                  NOMINAL DENSITY(LB/IN**3)              0.0025
       NOMINAL VAPOR PRESSURE(PSIA)         0.0                     NOMINAL VAPOR PRESSURE(PSIA)          25.0

       MAX PROPELLANT TEMP(DEGR)            0.0                     MAX PROPELLANT TEMP(DEGR)             40.0
       MAX TEMP DENSITY(LB/IN**3)           0.0000                  MAX TEMP DENSITY(LB/IN**3)             0.0025
       MAX TEMP VAPOR PRESSURE(PSIA)        0.0                     MAX TEMP VAPOR PRESSURE(PSIA)         25.0

       MIN PROPELLANT TEMP(DEGR)            0.0                     MIN PROPELLANT TEMP(DEGR)             40.0
       MIN TEMP DENSITY(LB/IN**3)           0.0000                  MIN TEMP DENSITY(LB/IN**3)             0.0025
       MIN TEMP VAPOR PRESSURE(PSIA)        0.0                     MIN TEMP VAPOR PRESSURE(PSIA)         25.0
```

ENGINE SIZE,WEIGHT,& PERFORMANCE SUMMARY FOR STAGE #1
EXPANDER CYCLE
CONVERGENT NOZZLE IS REGEN COOLED (MILLED SLOT CONSTRUCTION)
NOZZLE IS REGEN COOLED (TUBE CONSTRUCTION)
PROPELLANT IS LH2

.. ENGINE DIMENSIONS (INCHES) ...

THROAT DIAMETER	7.43
REACTOR SUPPORT DIAMETER	36.21
NOZZLE EXIT DIAMETER	166.10
NOZZLE EXTENSION ATTACH DIAM	18.19
CONVERGENT NOZZLE LENGTH	12.00
CONV. NOZZLE STRUCTURAL THICK.	1.169
GAS SIDE WALL THICKNESS	0.248
NOZZLE EXTENSION THICKNESS	0.010
SECOND NOZZLE EXTENSION THICKNESS	0.100
NOZZLE EXIT AREA RATIO	500.00
CONTRACTION RATIO	15.03
NOZ EXTENSION ATTCH AREA RATIO	6.00
SECOND NOZ EXT ATTACH AREA RATI	150.00
NOZZLE LENGTH/(MIN RAO LENGTH)	1.187
NOZZLE LENGTH	328.91
MOUNT LENGTH	2.00

.. ENGINE WEIGHTS (POUNDS) ...

NOZZLE EXTENSION	401.81
SECOND NOZZLE EXT	598.38
CONVERGENT NOZZLE	174.52
MAIN FUEL VALVE	387.35
TCA SUPPORT HARDWARE	616.66
SINGLE NOZZLE & HARDWARE	2178.72
THRUST MOUNT	1684.54
GIMBAL + POWER SUPPLY	302.77
ENGINE BAY LINES	210.71

... PERFORMANCE ...

DELIVERED ISP(VAC),SEC	912.94
IDEAL ISP(ODE),SEC	933.79
DELIVERED CSTAR,FT/SEC	16494.
IDEAL CSTAR,FT/SEC	16709.
CHAMBER PRESSURE,PSIA	1000.
THRUST PER ENGINE(VAC),LBF	75000.
TOTAL VAC THRUST,LBF	75000.
BURN TIME,SEC	3600.00
OVERALL EFFICIENCY	0.978
ENERGY RELEASE EFFICIENCY	0.987
NOZZLE EFFICIENCY	0.991
KINETIC EFFICIENCY	1.000
BARRIER COOLING EFFICIENCY	0.987
BOUNDARY LAYER EFFICIENCY	0.996
DIVERGENCE EFFICIENCY	0.996
FOR 1 ENGINES	
OXIDIZER FLOWRATE,LB/SEC	0.00
FUEL FLOWRATE,LB/SEC	84.53
TOTAL FLOWRATE,LB/SEC	84.53
CORE TEMPERATURE,DEG R	4860.
BARRIER TEMPERATURE,DEG R	1630.
ENGINE MIXTURE RATIO	0.00
FUEL FILM COOLING FRACTION	0.03

THE FOLLOWING IS THE REGENERATIVE COOLING SUMMARY FOR STAGE #1

THE ENGINE IS A FUEL COOLED
CONVENTIONAL EXPANSION NOZZLE

STATIONS 1 THROUGH 6 ARE BOUNDS TO THE 5 16.709 INCH LONG NOZZLE SECTIONS
STATIONS 6 THROUGH 11 ARE BOUNDS TO THE 5 3.213 INCH LONG CONVERGENT CHAMBER SECTIONS
STATIONS 11 THROUGH 11 ARE BOUNDS TO THE 0 0.000 INCH LONG CYLINDRICAL CHAMBER SECTIONS

GAS WALL THICKNESS = 0.248
GAS WALL THERMAL CONDUCTIVITY =.00039000 (BTU/IN SEC DEGR)
GAS WALL MAXIMUM OPERATING TEMPERATURE= 1460. (DEG R)

STATION	P	TB	W	V	Q	TCW	TGW	HG	HC	E	TGAS
1	.172E+04	.811E+02	.158E+01	.197E+02	.351E-02	0.102E+03	.104E+03	.197E-04	.170E-03	.150E+03	.283E+03
2	.172E+04	.813E+02	.128E+01	.299E+02	.669E-02	0.110E+03	.114E+03	.316E-04	.235E-03	.100E+03	.326E+03
3	.172E+04	.815E+02	.986E+00	.506E+02	.147E-01	0.123E+03	.133E+03	.570E-04	.352E-03	.600E+02	.390E+03
4	.172E+04	.820E+02	.690E+00	.104E+03	.407E-01	0.149E+03	.174E+03	.125E-03	.612E-03	.302E+02	.501E+03
5	.172E+04	.834E+02	.395E+00	.321E+03	.177E+00	0.215E+03	.328E+03	.400E-03	.134E-02	.106E+02	.769E+03
6	.149E+04	.898E+02	.100E+00	.581E+04	.177E+01	0.203E+03	.133E+04	.591E-02	.156E-01	.100E+01	.163E+04
7	.149E+04	.903E+02	.176E+00	.190E+04	.129E+01	0.350E+03	.117E+04	.281E-02	.498E-02	.248E+01	.163E+04
8	.149E+04	.909E+02	.251E+00	.936E+03	.934E+00	0.457E+03	.105E+04	.161E-02	.255E-02	.462E+01	.163E+04
9	.149E+04	.914E+02	.327E+00	.557E+03	.694E+00	0.530E+03	.971E+03	.105E-02	.158E-02	.743E+01	.163E+04
10	.149E+04	.920E+02	.402E+00	.370E+03	.531E+00	0.581E+03	.918E+03	.746E-03	.109E-02	.109E+02	.163E+04
11	.149E+04	.925E+02	.478E+00	.263E+03	.418E+00	0.616E+03	.882E+03	.559E-03	.798E-03	.150E+02	.163E+04

DELTA T= 11.3
DELTA P= -235.3
NOZZLE DELTA T = 9.7
NOZZLE DELTA P = -235.2
ADAPTER DELTA T = 1.6
ADAPTER DELTA P = -0.1
TOTAL HEAT TRANSFER = 656.9 (BTU/SEC)

P - COOLANT PRESSURE (PSIA)
TB - COOLANT BULK TEMPERATURE (DEGR)
W - COOLANT CHANNEL WIDTH (IN)
V - COOLANT VELOCITY (IN/SEC)
Q - HEAT FLUX (BTU/IN**2 SEC)
TCW - TEMPERATURE OF COOLANT WALL (DEGR)
TGW - TEMPERATURE OF GAS WALL (DEGR)
HG - GAS SIDE HEAT TRANSFER COEFF (BTU/IN**2 SEC DEGR)
HC - COOLANT SIDE HEAT TRANSFER COEFF (BTU/IN**2 SEC DEGR)
E - LOCAL AREA RATIO (-)
TGAS - COMBUSTION GAS TEMPERATURE (DEGR)

PRESSURE AND TEMPERATURE SCHEDULES FOR STAGE #1
EXPANDER CYCLE

	PRESSURE(PSIA) FUEL		OXIDIZER	TEMPERATURE(DEG R) FUEL		OXIDIZER	
... PRESSURANT ...							
MAX STORAGE	4365.0		4365.0	550.0		550.0	
VENT	154.9		0.0	60.0		0.0	(SATURATION TEMP OF PROPELLANT)
ULLAGE	140.8		0.0	—		—	
... PROPELLANT ...							
TANK PROPELLANT	140.8		0.0	40.0		0.0	
MAIN PUMP INLET	50.0-		0.0	40.0		0.0	
MAIN VALVE INLET	1800.7		0.0	81.6		0.0	
MAIN VALVE OUTLET	1721.2		0.0	81.6		0.0	
TIE TUBE OUTLET	1471.2		—	860.0		—	
REGEN OUTLET (REFL I	1485.9		—	92.9		—	
REFLECTOR OUTLET	1460.9		—	175.6		—	
REACTOR INLET		1135.1			343.0		
REACTOR CORE		1000.0			4860.0		
TURBINE INLET		1459.6			583.8		
TURBINE OUTLET		813.1			485.5		

.. COMPONENT PRESSURE/TEMPERATURE CHANGES ..

	PRESSURE CHANGES (PSID)			TEMPERATURE CHANGES (DEG R)		
ACQUISITION DEVICE	0.0		0.0			
FEED LINE	90.8		0.0	0.0		0.0
MAIN PUMP	1659.9		0.0	41.6		0.0
MAIN VALVE	79.5		0.0	0.0		0.0
TIE TUBES	250.0		—	778.5		—
REGEN JACKET	235.3		—	11.3		—
REFLECTOR	25.0		—	82.7		—
TURBINE		646.5			98.3	

FLOWRATE SCHEDULE (LB/SEC) FOR STAGE #1
EXPANDER CYCLE

	FUEL		OXIDIZER
TANK OUTFLOW	84.528		0.000
MAIN PUMP - EACH	42.264		0.000
MAIN VALVE	84.528		0.000
TOTAL TIE TUBES	24.646		—
REGEN JACKET INFLOW	59.883		—
NOZZLE BARRIER COOLING		2.376	
REGEN/REFL OUTLET TO CORE	40.830		—
TURBINE - EACH		20.661	
TURBINE TO CORE	41.323		0.000
STORED PRESSURANT (AVE)		0.16	
CORE	82.152		----

REACTOR OPERATING CHARACTERISTICS AND MASSES

REACTOR OPERATING CHARACTERISTICS

TOTAL COOLANT FLOW	82.15	LB/SEC
REACTOR POWER	1624.56	MW
CORE FLOW AREA	195.15	IN2
CORE MASS FLOW RATE	0.42	LB/IN2
NUMBER OF FUEL ELEMENTS	1307.77	
NUMBER OF SUPPORT ELEMENTS	253.96	
CHAMBER TEMPERATURE	4860.00	DEG R
CHAMBER PRESSURE	1000.00	PSIA
CHAMBER ENTHALPY	18648.66	BTU/LB
CORE INLET TEMPERATURE	342.98	DEG R
CORE INLET PRESSURE	1135.09	PSIA
CORE INLET ENTHALPY	1077.43	BTU/LB
HEAT PICKUP PER TIE TUBE	0.31	MW/TUBE
HEAT PICKUP IN TIE TUBES	74634.30	BTU/S
FRACTIONAL HEAT PICKUP IN NOZZLE	0.00	
HEAT PICKUP IN NOZZLE	656.89	BTU/S
FRACTIONAL HEAT PICKUP IN REFLECTOR	0.01	
HEAT PICKUP IN REFLECTOR	18789.01	BTU/S
FRACTIONAL CENTRAL SHIELD HEAT PICKUP	0.00	
CENTRAL SHIELD HEAT PICKUP	2664.34	BTU/S
FRACTIONAL EXTENSION SHIELD HEAT PICKUP	0.00	
EXTENSION SHIELD HEAT PICKUP	477.43	BTU/S
PEAK CHANNEL WALL TEMPERATURE	4961.60	DEG R
PEAK FUEL TEMPERATURE	5070.70	DEG R

REACTOR DIMENSIONS

CORE LENGTH	52.00	IN
FUEL ELEMENT CHANNEL DIAMETER	0.10	IN
VOID FRACTION OF FUEL ELEMENTS	0.30	
PEAK TO AVERAGE CHANNEL FACTOR	1.20	
CORE EFFECTIVE DIAMETER	31.29	IN
CORE DIAMETER	32.93	IN
LATERAL SUPPORT DIAMETER	36.21	IN
STRUCTURE OD	38.41	IN
REFLECTOR OD	47.98	IN
PRESSURE VESSEL ID	48.30	IN
PRESSURE VESSEL OD	49.73	IN
THICKNESS OF BATH SHIELD	12.43	IN
THICKNESS OF LEAD SHIELD	1.31	IN
PRESSURE VESSEL LENGTH	101.53	IN
FUEL VOLUME	23316.89	IN3

REACTOR MASSES

FUEL MASS	3217.73	LB
SUPPORT MASS	1007.09	LB
CORE PERIPHERY MASS	368.59	LB
LATERAL SUPPORT MASS	339.67	LB
STRUCTURE MASS	698.49	LB
REFLECTOR MASS	2265.43	LB
HOT END HARDWARE MASS	121.59	LB
AFT REFLECTOR MASS	65.81	LB
CORE INLET PLENUM MASS	169.55	LB
SUPPORT PLATE MASS	557.39	LB
LATERAL SUPPORT FORWARD MASS	44.60	LB
REFLECTOR HARDWARE FORWARD MASS	116.58	LB

SUPPORT PLATE PLENUM MASS	39.07	LB
INSTRUMENTATION RING MASS	32.61	LB
FORWARD REFLECTOR HARDWARE MASS	23.10	LB
SUBTOTAL CORE A	9067.29	LB
FLOW BAFFLE MASS	107.71	LB
FLOW BAFFLE 1 MASS	197.34	LB
SAFETY RODS	780.00	LB
TOTAL CORE SUBSYSTEM MASS	10152.34	LB
PRESSURE VESSEL A MASS	795.33	LB
PRESSURE VESSEL B MASS	300.85	LB
PRESSURE VESSEL DOME MASS	138.01	LB
NOZZLE/REACTOR ADAPTER MASS	96.15	LB
TOTAL PRESSURE VESSEL MASS	1330.33	LB
BATH CENTRAL SHIELD MASS	1061.04	LB
BATH PERIPHERAL SHIELD MASS	744.11	LB
BATH PERIPHERAL SHIELD 2 MASS	259.85	LB
LEAD CENTRAL SHIELD MASS	380.99	LB
LEAD PERIPHERAL SHIELD MASS	0.20	LB
LEAD PERIPHERAL SHIELD 2 MASS	0.09	LB
PERIPHERAL SHIELD PLATE MASS	40.93	LB
TOTAL SHIELD MASS	2487.21	LB
REACTOR MASS w/o SHIELD	11482.68	LB
REACTOR MASS w/ SHIELD	13969.89	LB

* * * TPA SUMMARY FOR STAGE #1 * * *

EXPANDER CYCLE

2 PROPELLANT FEED LEGS

TPA SIZE/WT/PERFORMANCE IS USER DEFINED

... FUEL PUMP ...

PUMP SPEED (RPM)	40356.
ROOT STRESS SPEED LIMIT(RPM)	46217.
SPECIFIC SPEED	704.
SUCTION SPECIFIC SPEED	20000.
NUMBER OF PUMP STAGES	1.
NET POS SUCTION PRESSURE(PSIA)	25.00
ACCELERATION HEAD(PSIA)	0.00
PUMP OUTLET PRESSURE(PSIA)	1800.69
VOLUMETRIC FLOWRATE(GPM)	4235.39
MASS FLOWRATE(LBM/SEC)	42.26
PUMP HORSEPOWER(HP)	6538.14
PUMP EFFICIENCY	0.661
PUMP DIAMETER(IN)	10.23
PUMP WT.(LB) - EACH PUMP	100.41

... TURBINE ...

ADMISSION FRACTION	1.000
EFFICIENCY	0.685
PRESSURE RATIO	1.795
MASS FLOWRATE(LB/SEC)	20.66
DIAMETER(IN)	5.97
NUMBER OF TURBINE STAGES	2.
BLADE ROOT STRESS LIMIT(PSI)	52309.
SPECIFIC SPEED	30.
TURBINE SPEED(RPM)	40356.
TURBINE WT(LB) - EACH TURBINE	35.57
TURBINE ANNULUS AREA(IN2)	17.764
U OVER C	0.37
INLET MACH NUMBER	0.62

... TPA ...

TPA START SYSTEM WT.	0.00
GAS GENERATOR/PREBURNER WT.	0.00
IGNITION SYSTEM WT.	32.24
HOT GAS MANIFOLD WT.	0.00
GEARBOX WT.	0.00
TPA WT.	271.95

.. STAGE #1 WEIGHTS (POUNDS) ...

AFT TANK	27.58
FORWARD TANK	4897.58
PRESSURE TANK	8063.91
TANK CONSTRUCTION WEIGHT	9092.35
TANK LINES	21.42
AFT SKIRT	354.59
FORWARD SKIRT	107.30
TANK MOUNT	0.00
STRUCTURAL WALL	5.73
PRESSURE TANK INSULATION	0.00
FUEL TANK INSULATION	237.41
OXIDIZER TANK INSULATION	60.79
FUEL ACQUISITION SYSTEM	11.28
OXIDIZER ACQUISITION SYSTEM	0.00
PRESSURANT CONTROL HARDWARE	57.13
ENGINE WEIGHTS:	
1 REACTOR	11482.68
1 TOTAL SHIELD	2487.21
1 NOZZLE + HARDWARE	2178.72
1 THRUST MOUNT(S)	1684.54
1 GIMBAL SYSTEM(S)	96.00
1 ENGINE BAY LINE(S)	210.71
1 GIMBAL POWER SUPPLY	206.77
2 IGNITION SYSTEM(S)	32.24
1 HOT GAS MANIFOLD(S)	0.00
2 TPA ASSY(S)	271.95
1 GEARBOX(S)	0.00
2 TPA START SYSTEM(S)	0.00
1 GAS GENERATOR/PREBURNER(S)	0.00
NON-NUCLEAR WEIGHT MARGIN	93.62
TOTAL ENGINE WEIGHT	18744.44
FLIGHT FUEL BOILOFF	0.00
FLIGHT OXIDIZER BOILOFF	0.00
EXPENDABLE WEIGHT	0.00
MISCELLANEOUS WEIGHT	0.00
USER DEFINED WEIGHT	0.00
TOTAL INERT WEIGHT	41681.50
INTERSTAGE WEIGHT	0.00
BURNED FUEL	8000.00
BURNED OXIDIZER	0.00
FUEL RESIDUAL	8.06
OXIDIZER RESIDUAL	0.00
STORED PRESSURANT	574.96

MISC ON-BOARD FUEL	0.00
MISC ON-BOARD OXIDIZER	0.00
GROSS IGNITION WEIGHT	50264.52
GROSS BURNOUT WEIGHT	42264.52
HOLD TIME FUEL BOILOFF	0.00
HOLD TIME OX BOILOFF	0.00

LUNAR LH2 NUCLEAR ROCKET

**** VEHICLE SUMMARY ****

	STAGE #1
..DIMENSIONS,IN..	
STAGE DIAMETER	100.00
NOZZLE EXIT DIAMETER	166.10
NUMBER OF NOZZLES	1
STAGE LENGTH	889.06
PAYLOAD LENGTH	0.00
TOTAL VEH LENGTH	889.06
..PERFORMANCE..	
PROPELLANT	LO2/LH2
THRUST,VACUUM DELIVERED,LBF	75000.0
PC,PSIA	1000.0
USABLE PROPELLANT MR	0.00
NOZZLE AREA RATIO	500.00
BURN TIME,SEC	3600.00
ISP,VACUUM DELIVERED,SEC	912.9
ISP EFFICIENCY	0.978
CORE PROP. FLOW RATE,LB/SEC	82.15

OUTPUT FOR SINGLE PUMP AT REDUCED THRUST

PRESSURE AND TEMPERATURE SCHEDULES FOR STAGE #1
FOR ONE PUMP AT REDUCED THRUST LEVEL 60000.
EXPANDER CYCLE

	PRESSURE(PSIA) FUEL	PRESSURE(PSIA) OXIDIZER	TEMPERATURE(DEG R) FUEL	TEMPERATURE(DEG R) OXIDIZER	
... PRESSURANT ...					
MAX STORAGE	4365.0	4365.0	550.0	550.0	
VENT	154.9	0.0	60.0	0.0	(SATURATION TEMP OF PROPELLANT)
ULLAGE	140.8	0.0	——	——	
... PROPELLANT ...					
TANK PROPELLANT	140.8	0.0	40.0	0.0	
MAIN PUMP INLET	50.0	0.0	40.0	0.0	
MAIN VALVE INLET	1690.2	0.0	76.1	0.0	
MAIN VALVE OUTLET	1610.7	0.0	76.1	0.0	
TIE TUBE OUTLET	1360.7	——	882.0	——	
REGEN OUTLET (REFL I	1451.6	——	87.0	——	
REFLECTOR OUTLET	1426.6	——	169.4	——	
REACTOR INLET	1135.6		351.3		
REACTOR CORE	1000.0		4860.0		
TURBINE INLET	1386.4		594.4		
TURBINE OUTLET	848.1		509.1		

.. COMPONENT PRESSURE/TEMPERATURE CHANGES ..

	PRESSURE CHANGES (PSID) FUEL	PRESSURE CHANGES (PSID) OXIDIZER	TEMPERATURE CHANGES (DEG R) FUEL	TEMPERATURE CHANGES (DEG R) OXIDIZER
ACQUISITION DEVICE	0.0	0.0		
FEED LINE	90.8	0.0	0.0	0.0
MAIN PUMP	1549.4	0.0	36.1	0.0
MAIN VALVE	79.5	0.0	0.0	0.0
TIE TUBES	250.0	——	805.8	——
REGEN JACKET	159.1	——	10.9	——
REFLECTOR	25.0	——	82.3	——
TURBINE	538.3		85.3	

FLOWRATE SCHEDULE (LB/SEC) FOR STAGE #1
EXPANDER CYCLE

	FUEL		OXIDIZER
TANK OUTFLOW	67.951		0.000
MAIN PUMP	67.951		0.000
MAIN VALVE	67.951		0.000
TOTAL TIE TUBES	19.747		——
REGEN JACKET INFLOW	48.204		——
NOZZLE BARRIER COOLING		2.128	
REGEN/REFL OUTLET TO CORE	32.714		——

TURBINE		33.109	
TURBINE TO CORE	33.109		0.000
STORED PRESSURANT (AVE)		0.14	
CORE	65.824		----

* * * TPA SUMMARY FOR STAGE #1 * * *
SUMMARY FOR TPA AT THRUST LEVEL FRACTION 0.80
EXPANDER CYCLE
SINGLE SHAFT TPA

... FUEL PUMP ...

PUMP SPEED (RPM)	40428.
ROOT STRESS SPEED LIMIT(RPM)	46223.
SPECIFIC SPEED	938.
SUCTION SPECIFIC SPEED	20000.
NUMBER OF PUMP STAGES	1.
NET POS SUCTION PRESSURE(PSIA)	25.00
ACCELERATION HEAD(PSIA)	0.00
PUMP OUTLET PRESSURE(PSIA)	1690.21
VOLUMETRIC FLOWRATE(GPM)	6787.09
MASS FLOWRATE(LBM/SEC)	67.95
PUMP HORSEPOWER(HP)	9143.20
PUMP EFFICIENCY	0.710
PUMP DIAMETER(IN)	10.23
PUMP WT.(LB)	100.41

... TURBINE ...

ADMISSION FRACTION	1.000
EFFICIENCY	0.700
PRESSURE RATIO	1.635
MASS FLOWRATE(LB/SEC)	33.11
DIAMETER(IN)	5.97
NUMBER OF TURBINE STAGES	2.
BLADE ROOT STRESS LIMIT(PSI)	52322.
SPECIFIC SPEED	72.
TURBINE SPEED(RPM)	40428.
TURBINE WT(LB)	35.57
TURBINE ANNULUS AREA(IN2)	17.764

... TPA ...

TPA START SYSTEM WT.	0.00
GAS GENERATOR/PREBURNER WT.	0.00
IGNITION SYSTEM WT.	16.12
HOT GAS MANIFOLD WT.	0.00
GEARBOX WT.	0.00
TPA WT.	135.98

VEHICLE SUMMARY

THRUST LEVEL =	75000.0	lbf
CHAMBER PRESSURE =	1000.0	psia
CHAMBER TEMPERATURE =	4860.0	deg R
NOZZLE EXIT AREA RATIO =	500.0	
REACTOR		
COMPOSITE FUEL		
REACTOR WEIGHT	11482.7	lbm
SHIELD WEIGHT	2487.2	lbm
REACTOR DIAMETER	49.7	in
REACTOR LENGTH	52.0	in
CORE PROPELLANT MASS FLOW	82.2	lbm/sec
NOZZLE		
CONVERGING NOZZLE WEIGHT	174.5	lbm
NOZZLE EXTENSION WEIGHT	401.8	lbm
SECOND NOZZLE EXTENSION WEIGHT	598.4	lbm
TOTAL NOZZLE WEIGHT	1174.7	lbm
AREA RATIO	500.0	
THROAT DIAMETER	7.4	in
EXIT DIAMETER	166.1	in
NOZZLE LENGTH	328.9	in
DELIVERED VACUUM ISP	912.9	sec
DELIVERED THRUST	75000.0	lbf
TURBOPUMP ASSEMBLY (TOTAL FOR ALL FEED LEGS)		
MAIN FUEL PUMP WEIGHT	200.8	lbm
MAIN OX PUMP WEIGHT	0.0	lbm
TURBINE WEIGHT	71.1	lbm
TPA IGNITION WEIGHT	32.2	lbm
MISC. HARDWARE WEIGHTS		
THRUST MOUNT	1684.5	lbm
SUPPORT HARDWARE	616.7	lbm
ENGINE LINES	210.7	lbm
MAIN VALVE	387.3	lbm
GIMBAL + POWER SUPPLY	302.8	lbm
SUBTOTAL		
MARGIN	93.6	lbm
TOTAL NONNUCLEAR WEIGHT	4774.6	lbm
TOTAL ENGINE SYSTEM		
TOTAL ENGINE WEIGHT	18744.4	lbm
TOTAL ENGINE WEIGHT WITHOUT SHIELD	16257.2	lbm
THRUST/WEIGHT RATIO WITH SHIELD	4.0	lbf/lbm
THRUST/WEIGHT RATIO WITHOUT SHIELD	4.6	lbf/lbm
PUMP-OUT CONDITIONS		
PUMP-OUT THRUST	60000.0	lbf
PUMP-OUT CHAMBER PRESSURE	1000.0	psia
PUMP-OUT CHAMBER TEMPERATURE	4860.0	deg R

```
WARNING

                 THE FOLLOWING WARNINGS OCCUR FOR STAGE 1

TWO PHASE FLUID ENCOUNTERED IN REGEN

CR = 15.026          RECOMMENDED RANGE = 1.5 TO 4

NOZZLE EXIT DIAM =  166.1     STAGE DIAM =  100.0

AXIAL BUCKLING DESIGNS STRUCTURAL WALL THICKNESS
HOOP STRESS DESIGNS AFT TANK WALL THICKNESS
HOOP STRESS DESIGNS  FORWARD TANK WALL THICKNESS
AFT TANK ULLAGE INCREASED BY GEOMETRY CONSTRAINT

GAS PHASE ENCOUNTERED IN REGEN JACKET
TPA CALCULATIONS TERMINATED BY ACHIEVING DESIRED ACCURACY

END NOMINAL STAGE DESIGN
```

5.0 MODEL VERIFICATION/COMPARISON

The sample case NESS NTP engine system design, discussed in Section 4.0, was compared to past preliminary engine system designs to support in verification of the models. Since no past detailed ENABLER-based NTP engine system designs are available that incorporate state-of-the-art engine system technologies, a comparison to similar, but not exact, engine system designs was undertaken. The 75,000 lbf, 1000 psi chamber pressure, composite fueled, 2700°K (4860°R) chamber temperature, 500:1 area ratio nozzle sample case was compared to a similar Rocketdyne NTP engine system design and a past ELES-NTP engine system design that are described in References 2-3 and 5-1. The past ELES-NTP engine system design example did not incorporate an integrated ENABLER reactor system design, but included a reactor system design that only approximated in matching engine system cycle parameters.

Tables 5-1, 5-2, and 5-3 compare the NESS sample design case to similar Rocketdyne and/or past ELES-NTP engine system designs. Table 5-1 compares key engine cycle parameters of the NESS sample case design to the Rocketdyne and ELES-NTP designs. One key observation is that the NESS design exhibits a delivered Isp of approximately 1% lower than than that associated with the other designs. This is attributed to the fact that the integrated NESS model more accurately calculates nozzle cooling losses. It was found that film cooling of the nozzle wall was required to keep its maximum wall temperature at or under the acceptable limit of 1460°R. Table 5-4 shows the effect of wall temperature on engine system performance as predicted by NESS. The ELES-NTP did not properly model this effect. It is unknown if the Rocketdyne engine design properly represents this integrated design effect. The reduced Isp also increased the engine system flow rate slightly to offset this effect.

The NESS program also more accurately models the pressure and temperature drops associated with cooling the nozzle and reactor system. This corresponds to the difference in the cycle pressures, temperatures, and turbopump operating parameters compared to the other referenced designs.

Engine system and component weight comparisons are presented in Tables 5-2 and 5-3. The reactor weight for the NESS design case is reduced 3.6% from the past ELES-NTP design. It is believed that this reduction in weight (and size) more accurately represents the reactor system because with the NESS model the reactor is sized to take advantage of heat captured by the coolant before it enters the reactor. Likewise, the NESS integrated ENABLER reactor system module more accurately determines the reactor system weight and size for a given design point, when compared to past modeling methods, see References 2-3 and 5-1.

Table 5-1 Engine Cycle Parameter Comparison*

Parameter	Rocketdyne	SAIC - ELES NTP	SAIC NESS
Pump Flowrate (kg/s)	36.7	36.9	37.3
Pump Discharge Pres. (psia)	1,544	1,538.3	2,628.6
Turbine Flowrate, % Pump	50	50	50
Turbine Inlet Temp. (°K)	555.6	555.3	324.3
Turbine Inlet Pres. (psia)	1,412	1,416.8	1,459.6
Turbine Pressure Ratio	1.25	1.295	1.795
Reactor Inlet Pres. (psia)	1,130	1,255.4	1,135.1
Reactor Power, (MW)	1,645	-	1,624.6
Reactor Core Flowrate (kg/s)	36.7	36.9	37.3
Nozzle Chamber Temp (°K)	2,700	2,700	2,700
Nozzle Chamber Pres. (psia)	1,000	1,000	1,000
Nozzle Exit Diameter (m)	4.15	4.15	4.22
Nozzle Expansion Ratio	500	500	500
Specific Impulse-Vac (sec)	923	922.8	912.9
Pump Speed (rpm)	37,500	34,913	40,356

* Rocketdyne uses their Mark 25 type axial turbopump (4 stages); SAIC ELES-NTP used a single-stage centrifugal pump; SAIC NESS uses a 2-Stage centrifugal pump.

Table 5-2. Engine Component Weight Comparison*

Parameter	Rocketdyne	SAIC ELES-NTP	SAIC NESS
Specific Impulse - Vac (sec)	923	922.8	912.9
Reactor (kg)	5,824	5,823	5,208
Internal Shield (kg)	—	1,523	1,128
Nozzle Assembly (kg)	440	421	533
Turbopump Assembly (kg)	304	104	138
Nonnuclear Support Hardware (kg) - Lines, Values, Actuators, Instrumentation Thrust Structure	1,815	1,264	1,495

* Rocketdyne uses their Mark 25 type axial turbopump (4 stages); SAIC ELES-NTP used a single-stage centrifugal pump; SAIC NESS uses a 2-stage centrifugal pump.

Table 5-3. Detailed Weight Comparison Between NTP-ELES and NESS for the Sample Case

Component	Features	NTP-ELES	NESS	No.
Reactor	Fuel Type Reactor + Internal Shield Weight Reactor Diameter Reactor Length Chamber Temperature Chamber Pressure Propellant Mass Flow (core)	Composite 14500 lbm 51 in 102 in 4860 deg R 1000 psia 81.32 lbm/s	Composite 13969.9 lbm 49.7 in 101.5 in 4860 deg R 1000 psia 82.15 lbm/s	
Nozzle	Nozzle Weight •Nozzle Throat (regen cooled) •Nozzle (regen tubes) •Nozzle Extension Area Ratio Throat Diameter Exit Diameter Nozzle Length Delivered Vacuum Lap Delivered Thrust	974.7 lbm 76.5 lbm 417.6 lbm 480.6 lbm 500 7.38 in 163.7 in 324.2 in 922.3 sec 75000 lbf	1174.68 lbm 174.5 lbm 401.8 lbm 598.38 lbm 500 7.43 in 166.1 in 328.9 in 912.94 sec 75000 lbf	1
Turbopump Assembly (TPA)	Main Pump Turbine Weight Main Fuel Pump Weight TPA Ignition	69.9 lbm 196.8 lbm 32.2 lbm	71.1 lbm 200.8 lbm 32.2 lbm	2 2 2
Misc. Hardware Weight	Thrust Mount Thrust Support Hardware Engine Lines Main Valve Gimbal System	1624 lbm 1262.6 lbm 202.7 lbm 402.6 lbm 76.9 lbm	1684.5 lbm 616.66 lbm 210.7 lbm 387.3 lbm 302.77 lbm	1 1 2 2 1
Subtotal	Margin (2%) Total Nonnuclear Weight (=TPA+Misc. Hdw+Nozzle+2%)	96.84 lbm 4939.25 lbm	93.61 lbm 4774.32 lbm	
Total Engine System	Weight Length	19439.2 lbm 462.2 in	18744.2 lbm 466.4 in	
T/W		**3.858**	**4.001**	

Table 5-4. Effect of Wall Temperature on Performance*

Wall Temperature (°R)	Barrier Temperature (°R)	Isp (Sec.)	Fuel Film Cooling Fraction
1460	1630	912.9	0.03
1800	2106	915.9	0.03
2000	2429	917.5	0.02
2400	2892	919.4	0.02
2800	3418	921.2	0.02
3000	3651	921.9	0.02
3200	3864	922.4	0.02

* Core Temperature = 4860°R (2700°k)

The ELES-NTP reactor system weight was approximated by reading off a reactor power versus weight graph that can have some inherent inconsistencies. The increase in the NESS weight for the TPA is due to the more stressing operating conditions in which the turbopumps must perform to meet the increased pumping requirements of the NESS design when compared to the others. The increase in the NESS design nozzle weight is attributed to a more accurate nozzle weight calculation which has been embedded in NESS. The ELES-NTP design approach only estimated nozzle weight which was done by multiple program runs to represent the various design portions of the nozzle. These results were then summed together which approximated the engine weight. NESS now calculates nozzle weight using exact geometric equations from which weight is determined.

The nonnuclear support hardware weight for weight is somewhat higher for the NESS design than the ELES-NTP design. The NESS design weight is believed to be more accurate than the ELES-NTP design weight because it uses true design calculations derived by TRW, see Ref. 1-1, during the past NERVA program effort that have been adjusted for today's technologies, as discussed in Section 2.2.5. Additionally, the NESS nonnuclear support hardware weight calculations are more representative of an NTP engine system because it includes options such as those associated with a gimbal power supply which can be a significant weight factor for long NTP engine burns and a weight allocation associated with a lower pressure cooldown propellant coolant feed leg. The past ELES-NTP nonnuclear weight was estimated, based on a percentage of the reactor weight which was typical of the NERVA flight engine, which has a larger degree of uncertainty.

Overall engine system thrust-to-weight was determined for the NESS design to be 3.7% greater than that exhibited by the ELES-NTP design. It is felt that the NESS program accurately models representative designs of near-term solid core NTP engine systems to support preliminary design and mission studies.

6.0 CONCLUDING REMARKS

The NESS preliminary design analysis program characterizes a complete near-term solid core NTP engine system in terms of performance, weight, and size, and key operating parameters in detail for the overall system and its associated subsystem. The NESS program incorporates numerous state-of-the-art engine system technology design options and design features unique to NTP systems such as a multiple leg turbopump propellant feed system assembly and a low pressure cooldown propellant coolant feed system, for example. The NESS program is easy to use and is flexible to address various NTP engine system design options efficiently. Though an initial validation effort, the NESS program is deemed accurate to support preliminary engine and vehicle system design and mission analysis efforts.

Development of the NESS program is considered to be one of many key first steps required to support NTP development. Because of the modular nature of the NESS program, it has great potential for further upgrades in its design/technology option and analysis capabilities. Recommended future upgrade activities include: incorporation of other representative reactor system design modules such as for a particle bed and/or a next generation solid core reactor system; incorporate an axial turbopump model, include a top-off engine system cycle option and include a gas generator off-design cycle analysis capability; upgrade performance prediction correlations; include and upgrade materials option capability which considers radiation effects/compatibility; perform more detailed analysis code verification; and convert NESS to be operable on a personal computer. It is envisioned that NESS could be a key element which could be integrated into an advanced NTP engine system design workstation.

7.0 REFERENCES

1-1 Plebuch, R. K., J. R. McDougall, R. B. Spencer, and K. R. Wener, "Volume IV: Detailed Technical Report, Nuclear Rocket Engine Analysis," TRW Report No. 8423-6008-RL000, TRW Space Technology Laboratories, Redondo Beach, CA, March 1965.

1-2 Taylor, C. E., "Expanded Liquid Engine Simulation Computer Program – Technical Information Manual," Aerojet Report No. ELES-1984, Aerojet TechSystems Company, Sacramento, CA, August 1984.

1-3 Taylor, C. E., "Expanded Liquid Engine Simulation Computer Program – Programmer's Manual," Aerojet Report No. ELES-1984, Aerojet TechSystems Company, Sacramento, CA, December 1984.

1-4 Livingstone, J. M. and B. L. Pierce, "The ENABLER – Based on Proven NERVA Technology," Proceedings of the Eight Symposium on Space Nuclear Power Systems, Vol. 2, pp. 598-620, January 1991.

2-1 Nickerson, G. R., L. D. Dang, and D. E. Coats, "Two-Dimensional Kinetic Reference Computer Program – Engineering and Programming Manual, "Software and Engineering Associates, Inc., Contract No. NAS8-35931, Report No. SN63, April 1985

2-2 "JANNAF Rocket Engine Performance Prediction and Calculation Manual," CPIA Publication 246, April 1975.

2-3 "NASA Manned Lunar and Mars Mission Propulsion System Assessment Studies; Task Order No. 9, Nuclear Thermal Rocket (NTR) System Assessment Studies – Nuclear Engine System Weight Scaling Results," Inter-Office Memorandum from D. Pelaccio to M. Stancati/H. Feingold, Contract No. NAS3-25809, dated 9 April 1991.

2-4 Pieper, J. L., "ICRPC Liquid Propellant Thrust Chamber Performance Evaluation Manual," CPIA Publication 178, September 1968.

2-5 "SSME Orientation (Part A – Engine)," Space Transportation System Technical Manual, Course No. ME-110(A) RIR, Rockwell International Corporation, Rocketdyne Division, Contract No. NAS8-27980, 1 November 1984.

2-6 "Space Shuttle Main Engine," Space Transportation System Technical Manual, Rockwell International Corporation, Rocketdyne Division, Contract No. NAS8-27980, DPD No. 341 DR No. LS-090-1, 1 September 1983.

3-1 Lyon, L. L., "Performance of (U,Zr)C-Graphite (Composite) and of (U,Zr)C (Carbide) Fuel Elements in the Nuclear Furnace 1 Test Reactor," LA-5398-MS, Los Alamos National Laboratory.

3-2 Taub, J. M., "A Review of Fuel Element Development for Nuclear Rocket Engines," LA-5931, Los Alamos National Laboratory.

3-3 McCarthy, J. R. and H. Wolf, "Forced Convection Heat Transfer to Gaseous Hydrogen at High Heat Flux and High Pressure in a Smooth, Round, Electrically Heated Tank," American Rocket Society Journal p. 43, April 1960.

3-4 Taylor, M. F., "A Method of Correlating Local and Average Friction Coefficients for Both Laminar and Turbulent Flow of Gases Through a Smooth Tube with Surface to Fluid Bulk Temperature Ratios from 0.35 to 7.35," International Heat and Mass Transfer Shorter Communications, August 1967.

3-5 "Radiation Heating Rates for the Type C Components of the Preliminary Reference Design (939J723)," DRM-52852, Westinghouse Astronuclear Laboratory (currently Westinghouse AES), November 1970.

5-1 Pelaccio, D, C. Scheil and J. Livingstone, "Updated Solid-Core Nuclear Thermal Propulsion Engine Trades," AIAA Paper No. AIAA-91-3507. Presented at the AIAA/NASA/OAI Conference on Advanced SEI Technologies, Cleveland, OH, 4-6 September 1991.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1993	Final Contractor Report

4. TITLE AND SUBTITLE

Nuclear Engine System Simulation (NESS)
Volume I – Program User's Guide

5. FUNDING NUMBERS

WU-593-71
NAS3-25809

6. AUTHOR(S)

Dennis G. Pelaccio, Christine M. Scheil, and Lyman J. Petrosky

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Science Applications International Corporation
21151 Western Avenue
Torrance, California 90501–1724

8. PERFORMING ORGANIZATION REPORT NUMBER

E-7622

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR–191080

11. SUPPLEMENTARY NOTES

Project Manager, James T. Walton, Nuclear Propulsion Office, NASA Lewis Research Center, (216) 891–2175.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 20

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

An accurate, standalone, preliminary Nuclear Thermal Propulsion (NTP) engine system design analysis tool is required to support current and future Space Exploration Initiative (SEI) propulsion and vehicle design studies. Currently available NTP engine design models are those developed during the NERVA program in the 1960s and early 1970s and are highly unique to that design (see Ref. 1-1) or are modifications of current liquid propulsion system design models. To date, NTP engine-based liquid design models lack integrated design of key NTP engine design features, such as in the areas of reactor, shielding, multi-propellant capability, and multi-redundant pump feed fuel systems. Additionally, since the SEI effort is in the initial development stage, a robust, verified NTP analysis design tool could be of great use to the community. This effort developed an accurate, versatile NTP engine system design analysis program (tool), known as the Nuclear Engine System Simulation (NESS) program, to support ongoing and future engine system and stage design study efforts. In this effort, Science Applications International Corporation's (SAIC) NTP version of the Expanded Liquid Engine Simulation (ELES) program was modified extensively to include Westinghouse Electric Corporation's near-term solid-core reactor design model. The ELES program has extensive capability to conduct preliminary system design analysis of liquid rocket systems and vehicles. The program is modular in nature and is versatile in terms of modeling state-of-the-art component and system options as discussed in Refs. 1-2 and 1-3. The Westinghouse reactor design model, which was integrated in the NESS program, is based on the near-term solid-core ENABLER NTP reactor design concept (see Ref. 1-4). This program is now capable of accurately modeling (characterizing) a complete near-term solid-core NTP engine system in great detail, for a number of design options, in an efficient manner. The following discussion summarizes the overall analysis methodology, key assumptions, and capabilities associated with the NESS, presents an example problem, and compares the results to related NTP engine system designs. Initial installation instructions and program disks are in Volume 2 of the NESS Program User's Guide

14. SUBJECT TERMS

Nuclear propulsion; Computer program

15. NUMBER OF PAGES

122

16. PRICE CODE

A06

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

National Aeronautics and
Space Administration

Lewis Research Center
Cleveland, Ohio 44135

FOURTH CLASS MAIL

ADDRESS CORRECTION REQUESTED